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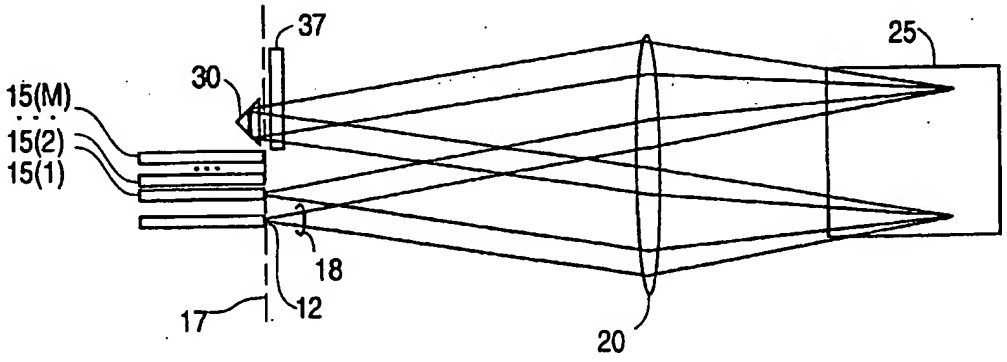

(57) Abstract: A wavelength router that selectively directs spectral bands between an input port (12) and output ports (15). The router includes a free-space optical train disposed between the input ports and said output ports, and a routing mechanism (30). The free-space optical train can include air-space elements (20, 25) or can be monolithic construction. The optical train includes a dispersive element (25) such as a diffraction grating, and is configured so that the light from the input port encounters the dispersive element twice before reaching the output ports. The routing mechanism (30) includes one or more routing elements and cooperates with the other elements (37) in the optical train to provide optical paths that couple subsets of the spectral bands to desired output ports.

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WAVELENGTH ROUTER

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of U.S. Patent Application No. 09/442,061, filed November 16, 1999, the entire disclosure of which (including attachments and appendices) is incorporated by reference in its entirety for all purposes:

BACKGROUND OF THE INVENTION

This application relates generally to fiber-optic communications and more specifically to techniques and devices for routing different spectral bands of an optical beam to different output ports. (or conversely, routing different spectral bands at the output ports to the input port).

The Internet and data communications are causing an explosion in the global demand for bandwidth. Fiber optic telecommunications systems are currently deploying a relatively new technology called dense wavelength division multiplexing (DWDM) to expand the capacity of new and existing optical fiber systems to help satisfy this demand. In DWDM, multiple wavelengths of light simultaneously transport information through a single optical fiber. Each wavelength operates as an individual channel carrying a stream of data. The carrying capacity of a fiber is multiplied by the number of DWDM channels used. Today DWDM systems employing up to 80 channels are available from multiple manufacturers, with more promised in the future.

In all telecommunication networks, there is the need to connect individual channels (or circuits) to individual destination points, such as an end customer or to another network. Systems that perform these functions are called cross-connects. Additionally, there is the need to add or drop particular channels at an intermediate point. Systems that perform these functions are called add-drop multiplexers (ADMs). All of these networking functions are currently performed by electronics – typically an electronic SONET/SDH system. However SONET/SDH systems are designed to process only a single optical channel. Multi-wavelength systems would require multiple SONET/SDH systems operating in parallel to process the many optical channels. This makes it difficult and expensive to scale DWDM networks using SONET/SDH technology.

The alternative is an all-optical network. Optical networks designed to operate at the wavelength level are commonly called "wavelength routing networks" or "optical transport networks" (OTN). In a wavelength routing network, the individual wavelengths in a DWDM fiber must be manageable. New types of photonic network elements operating at the wavelength level are required to perform the cross-connect, ADM and other network switching functions. Two of the primary functions are optical add-drop multiplexers (OADMs) and wavelength-selective cross-connects (WSXCs).

In order to perform wavelength routing functions optically today, the light stream must first be de-multiplexed or filtered into its many individual wavelengths, each on an individual optical fiber. Then each individual wavelength must be directed toward its target fiber using a large array of optical switches commonly called as optical cross-connect (OXC). Finally, all of the wavelengths must be re-multiplexed before continuing on through the destination fiber. This compound process is complex, very expensive, decreases system reliability and complicates system management. The OXC in particular is a technical challenge. A typical 40-80 channel DWDM system will require thousands of switches to fully cross-connect all the wavelengths. Opto-mechanical switches, which offer acceptable optical specifications are too big, expensive and unreliable for widespread deployment. New integrated solid-state technologies based on new materials are being researched, but are still far from commercial application.

Consequently, the industry is aggressively searching for an all-optical wavelength routing solution which enables cost-effective and reliable implementation of high-wavelength-count systems.

SUMMARY OF THE INVENTION

The present invention provides a wavelength router that allows flexible and effective routing of spectral bands between an input port and a set of output ports (reversibly, also between the output ports and the input port).

An embodiment of the invention includes a free-space optical train disposed between the input ports and said output ports, and a routing mechanism. The free-space optical train can include air-spaced elements or can be of generally monolithic construction. The optical train includes a dispersive element such as a diffraction grating, and is configured so that the light from the input port encounters the dispersive element twice before reaching any of the output ports. The routing mechanism includes one or more routing elements and cooperates with the other elements in the optical train to

provide optical paths that couple desired subsets of the spectral bands to desired output ports. The routing elements are disposed to intercept the different spectral bands after they have been spatially separated by their first encounter with the dispersive element.

The invention includes dynamic (switching) embodiments and static embodiments. In dynamic embodiments, the routing mechanism includes one or more routing elements whose state can be dynamically changed in the field to effect switching. In static embodiments, the routing elements are configured at the time of manufacture or under circumstances where the configuration is intended to remain unchanged during prolonged periods of normal operation.

In the most general case, any subset of the spectral bands, including the null set (none of the spectral bands) and the whole set of spectral bands, can be directed to any of the output ports. However, there is no requirement that the invention be able to provide every possible routing. Further, in general, there is no constraint on whether the number of spectral bands is greater or less than the number of output ports.

In some embodiments of the invention, the routing mechanism includes one or more retroreflectors, each disposed to intercept a respective one of the spectral bands after the first encounter with the dispersive element, and direct the light in the opposite direction with a controllable transverse offset. In other embodiments, the routing mechanism includes one or more tiltable mirrors, each of which can redirect one of the spectral bands with a controllable angular offset. There are a number of ways to implement the retroreflectors, including as movable rooftop prisms or as subassemblies including fixed and rotating mirrors.

In some embodiments, the beam is collimated before encountering the dispersive element, so as to result in each spectral band leaving the dispersive element as a collimated beam traveling at an angle that varies with the wavelength. The dispersed beams are then refocused onto respective routing elements and directed back so as to encounter the same elements in the optical train and the dispersive element before exiting the output ports as determined by the disposition of the respective routing elements. Some embodiments of the invention use cylindrical lenses while others use spherical lenses. In some embodiments, optical power and dispersion are combined in a single element, such as a computer generated holograph.

It is desirable to configure embodiments of the invention so that each routed channel has a spectral transfer function that is characterized by a band shape having a relatively flat top. This is achieved by configuring the dispersive element to

have a resolution that is finer than the spectral acceptance range of the individual routing elements. In many cases of interest, the routing elements are sized and spaced to intercept bands that are spaced at regular intervals. The bands are narrower than the band intervals, and the dispersive element has a resolution that is significantly finer than the band intervals.

According to other aspects of the invention, optical add-drop multiplexers (OADMs), wavelength-selective cross-connects (WSXCs), and drop-and-repeat OADMs can be constructed using wavelength routers in a variety of what could be referred to as a back-to-back or oppositely facing configurations. Each wavelength router, when in a "forward" mode has an input port and a plurality of output ports with the functionality of directing subsets of a plurality of spectral bands at the input port to desired output ports. The wavelength routers are reversible, so in a "backward" mode, the input port becomes an output port and the output ports become input ports, with the device having the functionality of combining light at the plurality of what are in the backward mode now considered input ports to exit at what is now in the backward mode considered the output port. For ease of description, however, the wavelength routers will be described in terms of having an input port and multiple output ports, regardless of which direction the wavelength router is facing relative to the light direction.

An optical add-drop multiplexer (OADM) according to an aspect of the invention includes first and wavelength routers where each wavelength router has an input port and a plurality of output ports. The first and second wavelength routers are connected in a back-to-back configuration. A first subset of the first wavelength router's output ports is in optical communication with a corresponding first subset of the second wavelength router's output ports, a second subset of the first wavelength router's output ports provide a drop functionality, and a corresponding second subset of the second wavelength router's output ports provide an add functionality. Thus, of light entering the first wavelength router's input port, selected spectral bands are passed to the second wavelength router and exit through the second wavelength router's input port, while selected spectral bands are dropped as terminated traffic or for further processing. The second wavelength router's output port can accept spectral bands as originating traffic, and these spectral bands are combined with the spectral bands that are passed from the first wavelength router to the second wavelength router, with the combined light exiting the second wavelength router's input port.

A wavelength-selective cross-connect (WSXC) according to an aspect of the invention includes first and second wavelength routers connected in a back-to-back configuration, and third and fourth wavelength routers connected in a back-to-back configuration. Light is considered to enter the input ports of the first and third wavelength routers, and to exit the input ports of the third and fourth wavelength routers. The output ports of each wavelength router include what are referred to as a through port and an exchange port.

The through ports of the first and second wavelength routers are in optical communication with each other, as are the through ports of the third and fourth wavelength routers. The exchange ports of the first and third wavelength routers are in optical communication with the exchange ports of the fourth and second wavelength routers, respectively. Thus, a first selected subset of the spectral bands entering the input ports of the first and third wavelength routers are passed through to exit the input ports of the second and fourth wavelength routers, respectively, while a second selected subset of the spectral bands entering the input ports of the first and third wavelength routers are exchanged, and exit the input ports of the fourth and second wavelength routers, respectively.

A protection switching configuration according to an aspect of the invention includes first and second wavelength routers connected in a back-to-back configuration, and third and fourth wavelength routers connected in a back-to-back configuration. Light traveling in one direction is considered to enter the input port of the first wavelength router and to exit the input port of the second wavelength router. Light traveling in the opposite direction is considered to enter the input port of the fourth wavelength router and to exit the input port of the third wavelength router. The output ports of each wavelength router include what are referred to as a through port and a loopback port.

The through ports of the first and second wavelength routers are in optical communication with each other, as are the through ports of the third and fourth wavelength routers. The loopback ports of the first and fourth wavelength routers are in optical communication with the loopback ports of the third and second wavelength routers, respectively. Thus, a first selected subset of the spectral bands entering the input ports of the first and fourth wavelength routers are passed through to the input ports of the second and third wavelength routers, respectively, while a second selected subset of the spectral bands entering the input ports of the first and fourth wavelength routers are

looped back, and exit the input ports of the third and second wavelength routers, respectively.

A drop-and-repeat OADM according to an aspect of the invention includes an OADM, with the addition of a splitting element such as a tap coupler or splitter having an input port and first and second output ports, and a combining element such as an optical coupler or combiner having first and second input ports and an output port. The splitting element's input port is in optical communication with the OADM's drop port, the splitting element's first output port is in optical communication with the combining element's first input port, and the combining element's output port is in optical communication with the OADM's add port. The second output port of the splitting element and the second input port of the combining element define the drop and add ports of the drop-and-repeat OADM.

A drop-and-repeat OADM according to an aspect of the invention includes a WSXC having first and second input ports and first and second output ports, with the addition of a splitting element such as a tap coupler or splitter having an input port and first and second output ports, and a combining element such as an optical coupler or combiner having first and second input ports and an output port. The splitting element's input port is in optical communication with the WSXC's second output port, the splitting element's first output port is in optical communication with the combining element's first input port, and the combining element's output port is in optical communication with the WSXC's second input port. The second output port of the splitting element and the second input port of the combining element define the drop and add ports of the drop-and-repeat OADM.

A further understanding of the nature and advantages of the present invention may be realized by reference to the remaining portions of the specification and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1A, 1B, and 1C are schematic top, side, and end views, respectively, of a wavelength router according to an embodiment of the invention that uses spherical focusing elements;

Figs. 2A and 2B are schematic top and side views, respectively, of a wavelength router according to another embodiment of the invention that uses spherical focusing elements;

Fig. 3 is a schematic top view of a wavelength router according to another embodiment of the invention that uses spherical focusing elements;

Figs. 4A and 4B show alternative implementations of a retroreflector, based on a movable rooftop prism, suitable for use with embodiments of the present invention;

Figs. 4C and 4D are side and top views of a rooftop prism array fabricated as a single unit;

Fig. 5A shows an implementation of a retroreflector, based on a movable mirror, suitable for use with embodiments of the present invention;

Figs. 5B and 5C are side and top views of an implementation of a retroreflector array, based on micromirrors, suitable for use with embodiments of the present invention;

Fig. 5D is a side view of an alternative implementation of a retroreflector array based on micromirrors;

Figs. 6A and 6B are schematic top and side views, respectively, of a wavelength router according to an embodiment of the invention that uses cylindrical focusing elements;

Figs. 7A and 7B are schematic top and side views, respectively, of a wavelength router according to another embodiment of the invention that uses cylindrical focusing elements;

Figs. 8A and 8B are schematic top and side end views, respectively, of a wavelength router according to an embodiment of the invention that combines spherical focusing power and dispersion in a single element;

Figs. 9A and 9B are schematic top and side views, respectively, of a wavelength router according to an embodiment of the invention that combines cylindrical focusing power and dispersion in a single element;

Figs. 10A and 10B are schematic top and side views, respectively, of a wavelength router according to an embodiment of the invention that uses a prism as the dispersive element;

Fig. 11 shows a representative control system for a wavelength router;

Fig. 12A shows a preferred band shape;

Figs. 12B and 12C show the differential path length for a representative path from Fig. 1A;

Fig. 13 is a schematic showing a combination of wavelength routers to provide an optical add-drop multiplexer (OADM);

Fig. 14 is a schematic showing a combination of wavelength routers to provide a wavelength-selective cross-connect (WSXC);

Fig. 15 is a schematic showing a combination of wavelength routers to provide protection switching in an optical multiplexed section shared protection ring (OMSSPRing) optical network; and

Figs. 16 and 17 are schematics showing embodiments of a drop-and-repeat OADM based on the OADM of Fig. 13 and the WSXC of Fig. 14, respectively.

DESCRIPTION OF SPECIFIC EMBODIMENTS

Introduction

The following description sets forth embodiments of an all-optical wavelength router according to the invention. Embodiments of the invention can be applied to network elements such as optical add-drop multiplexers (OADMs) and wavelength-selective cross-connects (WSXCs) to achieve the goals of optical networking systems.

The general functionality of the wavelength router is to accept light having a plurality of (say N) spectral bands at an input port, and selectively direct subsets of the spectral bands to desired ones of a plurality of (say M) output ports. Most of the discussion will be with reference to dynamic (switching) embodiments where the routing mechanism includes one or more routing elements whose state can be dynamically changed in the field to effect switching. The invention also includes static embodiments in which the routing elements are configured at the time of manufacture or under circumstances where the configuration is intended to remain unchanged during prolonged periods of normal operation.

The embodiments of the invention include a dispersive element, such as a diffraction grating or a prism, which operates to deflect incoming light by a wavelength-dependent amount. Different portions of the deflected light are intercepted by different routing elements. Although the incoming light could have a continuous spectrum, adjacent segments of which could be considered different spectral bands, it is generally contemplated that the spectrum of the incoming light will have a plurality of spaced bands.

The terms "input port" and "output port" are intended to have broad meanings. At the broadest, a port is defined by a point where light enters or leaves the system. For example, the input (or output) port could be the location of a light source (or detector) or the location of the downstream end of an input fiber (or the upstream end of an output fiber). In specific embodiments, the structure at the port location could include a fiber connector to receive the fiber, or could include the end of a fiber pigtail, the other end of which is connected to outside components. Most of the embodiments contemplate that light will diverge as it enters the wavelength router after passing through the input port, and will be converging within the wavelength router as it approaches the output port. However, this is not necessary.

The International Telecommunications Union (ITU) has defined a standard wavelength grid having a frequency band centered at 193,100 GHz, and another band at every 100 GHz interval around 193,100 GHz. This corresponds to a wavelength spacing of approximately 0.8 nm around a center wavelength of approximately 1550 nm, it being understood that the grid is uniform in frequency and only approximately uniform in wavelength. Embodiments of the invention are preferably designed for the ITU grid, but finer frequency intervals of 25 GHz and 50 GHz (corresponding to wavelength spacings of approximately 0.2 nm and 0.4 nm) are also of interest.

The ITU has also defined standard data modulation rates. OC-48 corresponds to approximately 2.5 GHz (actually 2.488 GHz), OC-192 to approximately 10 GHz, and OC-768 to approximately 40 GHz. The unmodulated laser bandwidths are on the order of 10-15 GHz. In current practice, data rates are sufficiently low (say OC-192 on 100 GHz channel spacing) that the bandwidth of the modulated signal is typically well below the band interval. Thus, only a portion of the capacity of the channel is used. However, when attempts are made to use more of the available bandwidth (say OC-768 on 100 GHz channel spacing), problems relating to the band shape of the channel itself arise. Techniques for addressing these problems will be described below.

Embodiments with Spherical Focusing Elements

Figs. 1A, 1B, and 1C are schematic top, side, and end views, respectively, of a wavelength router 10 according to an embodiment of the invention. The general functionality of wavelength router 10 is to accept light having a plurality of (say N) spectral bands at an input port 12, and selectively direct subsets of the spectral bands to desired ones of a plurality of (say M) output ports, designated 15(1 ... M). The output

ports are shown in the end view of Fig. 1C as disposed along a line 17 that extends generally perpendicular to the top view of Fig. 1A. The input and output ports are shown as communicating with respective input and output optical fibers, but it should be understood that the input port could also receive light directly from a light source, and the output ports could be coupled directly to optical detectors. The drawing is not to scale.

Light entering wavelength router 10 from input port 12 forms a diverging beam 18, which includes the different spectral bands. Beam 18 encounters a lens 20 which collimates the light and directs it to a reflective diffraction grating 25. Grating 25 disperses the light so that collimated beams at different wavelengths are directed at different angles back towards lens 20. Two such beams are shown explicitly and denoted 26 and 26' (the latter drawn in dashed lines). Since these collimated beams encounter the lens at different angles, they are focused at different points along a line 27 in a transverse focal plane. Line 27 extends in the plane of the top view of Fig. 1A.

The focused beams encounter respective ones of plurality of retroreflectors, designated 30(1 ... N), located near the focal plane. The beams are directed, as diverging beams, back to lens 20. As will be described in detail below, each retroreflector sends its intercepted beam along a reverse path that may be displaced in a direction perpendicular to line 27. More specifically, the beams are displaced along respective lines 35(1 ... N) that extend generally parallel to line 17 in the plane of the side view of Fig. 1B and the end view of Fig. 1C.

In the particular embodiment shown, the displacement of each beam is effected by moving the position of the retroreflector along its respective line 35(i). In other embodiments, to be described below, the beam displacement is effected by a reconfiguration of the retroreflector. It is noted that the retroreflectors are shown above the output ports in the plane of Fig. 1C, but this is not necessary; other relative positions may occur for different orientations of the grating or other elements.

The beams returning from the retroreflectors are collimated by lens 20 and directed once more to grating 25. Grating 25, on the second encounter, removes the angular separation between the different beams, and directs the collimated beams back to lens 20, which focuses the beams. However, due to the possible displacement of each beam by its respective retroreflector, the beams will be focused at possibly different points along line 17. Thus, depending on the positions of the retroreflectors, each beam is directed to one or another of output ports 15(1 ... M).

In sum, each spectral band is collimated, encounters the grating and leaves the grating at a wavelength-dependent angle, is focused on its respective retroreflector such that is displaced by a desired amount determined by the retroreflector, is collimated again, encounters the grating again so that the grating undoes the previous dispersion, and is focused on the output port that corresponds to the displacement imposed by the retroreflector. In the embodiment described above, the light traverses the region between the ports and the grating four times, twice in each direction.

This embodiment is an airspace implementation of a more generic class of what are referred to as free-space embodiments. In some of the other free space embodiments, to be described below, the various beams are all within a body of glass. The term "free-space" refers to the fact that the light within the body is not confined in the dimensions transverse to propagation, but rather can be regarded as diffracting in these transverse dimensions. Since the second encounter with the dispersive element effectively undoes the dispersion induced by the first encounter, each spectral band exits the router with substantially no dispersion.

Figs. 1A-1C show a quarter-wave plate 37 intercepting the light beams as they approach and leave retroreflectors 30(1...N). The quarter-wave plate is used to compensate for any polarization dependence of grating 25. In general, the light emerging from input port 12 can have arbitrary polarization. Thus, if the grating's efficiency coefficient differs significantly for two orthogonal polarization states, the overall transmission efficiency of the wavelength router can vary as a function of time to the extent that the polarization varies as a function of time, and as a function of wavelength if the different spectral bands have different polarizations. Fig. 1C shows schematically that the axis of the quarter-wave plate at 45° relative to the direction of line 27. More detail regarding the mechanism by which quarter-wave plate 37 reduces the polarization dependence of the wavelength router will be provided below. For present purposes, it suffices to note that the polarization dependence of wavelength router 10 can be reduced by use of quarter-wave plate 37. It is also possible to use a Faraday rotator to perform the function of the quarter-wave plate.

Figs. 2A and 2B are schematic top and side views, respectively, of a wavelength router, designated 10', according to an embodiment of the invention. The same reference numerals or primed or suffixed reference numerals will be used for elements corresponding to those in Figs. 1A-1C. This embodiment differs from the embodiment of Figs. 1A-1C in that it uses a transmissive diffraction grating 25' and a pair

of lenses 20a and 20b. Thus, this embodiment can be considered an unfolded version of the embodiment of Figs. 1A-1C.

Light entering wavelength router 10' from input port 12 forms diverging beam 18, which includes the different spectral bands. Beam 18 encounters first lens 20a, which collimates the light and directs it to grating 25'. Grating 25' disperses the light so that collimated beams at different wavelengths emerge from the beam and proceed. The collimated beams, one of which is shown, encounter second lens 20b, which focuses the beams. The focused beams encounter respective ones of plurality of retroreflectors 30(1 ... N), located near the focal plane. The beams are reflected, and emerge as diverging beams, back to lens 20b, are collimated and directed to grating 25'. Grating 25', on the second encounter, removes the angular separation between the different beams, which are then focused in the plane of output ports 15(1 ... M).

In the specific implementation, input port 12, lens 20a, grating 25', lens 20b, and the retroreflectors are spaced at approximately equal intervals, with the two lenses having equal focal lengths and the distance between the input port and the retroreflectors being four times (4x) the focal length. Thus the focal lengths and the relative positions define what is referred to as a "4f relay" between input port 12 and the retroreflectors, and also a 4f relay between the retroreflectors and the output ports. This configuration is not necessary, but is preferred. The optical system is preferably telecentric.

Fig. 3 is a schematic top view of a wavelength router 10" according to an embodiment of the invention. This embodiment is a solid glass embodiment that uses a concave reflector 40 in the place of lens 20 of the first embodiment (or lenses 20a and 20b in the second embodiment). Thus, this embodiment can be considered a further folded version of the embodiment of Figs. 1A-1C. As above, light entering wavelength router 10" from input port 12 forms diverging beam 18, which includes the different spectral bands. Beam 18 encounters concave reflector 40, which collimates the light and directs it to reflective diffraction grating 25. Grating 25 disperses the light so that collimated beams at different wavelengths are directed at different angles back toward reflector 40. Two such beams are shown explicitly, one in solid lines and one in dashed lines. Since these collimated beams encounter the reflector at different angles, they are focused at different points in a transverse focal plane.

The focused beams encounter retroreflectors 30(1 ... N) located near the focal plane. The operation in the reverse direction is as described in connection with the

embodiments above, and the beams follow the reverse path, which is displaced in a direction perpendicular to the plane of Fig. 3. Therefore, the return paths directly underlie the forward paths and are therefore not visible in Fig. 3. On this return path, the beams encounter concave reflector 40, reflective grating 25', and concave reflector 40, the final encounter with which focuses the beams to the desired output ports (not shown in this figure) since they underlie input port 12.

Rooftop-Prism-Based Retroreflector Implementations

Figs. 4A and 4B show alternative implementations of a retroreflector, based on a movable rooftop prism, suitable for use with embodiments of the present invention. The retroreflectors, designated 30a and 30b could be used to implement array 30(1 ... N) in the embodiments described above.

Fig. 4A shows schematically the operation of a retroreflector, designated 30a, that operates to displace an incoming beam by different amounts depending on displacement of the retroreflector transversely relative to the beam. The left portion of the figure shows the retroreflector in a first position. A second, downwardly displaced, position is shown in phantom. The right portion of the figure shows the retroreflector displaced to the second position, whereupon the reflected beam is displaced downwardly by an amount proportional to the retroreflector displacement. The retroreflector is shown as a rooftop prism, and the operation is based on total internal reflection. It is also possible to implement the retroreflector as a pair of mirrors in a V-shaped configuration. A retroreflector of this type has the property that while the reflected beam is offset from the incident beam by an amount that depends on the incident beam's offset relative to the prism's peak, the total path length is independent of the offset.

Fig. 4B shows schematically the operation of a retroreflector, designated 30b, that includes a rooftop prism element 50 and a pair of matched-index upper and lower plates 51 and 52 in a V-shaped configuration spaced slightly from the prism element. Displacement of the incoming beam is effected by selectively contacting prism element 50 with one or the other of plates 51 or 52. The left portion of the figure shows the prism element contacting upper plate 51, whereupon the input beam passes into the upper plate and is internally reflected by the upper plate and the lower surface of the prism element. The right portion of the figure shows the prism element contacting lower plate 52, whereupon the input beam is internally reflected by the upper surface of the prism element, passes into the lower plate, and undergoes internal reflection at the lower

surface of the lower plate. This retroreflector can be seen to provide a beam displacement that can be large relative to the prism element displacement.

Figs. 4C and 4D are side and top views of a rooftop prism array fabricated as a single unit. To maintain uniformity across the array, the rooftop prism array is first made as a single elongated prism element and attached to one end of a support plate. The top and bottom of this assembly is polished optically flat and slots 53 are cut through the prism and support plate assembly to define an array of individual prism elements 54 on respective support tines 55. Two stops 57a and 57b are placed, one above and one below this rooftop prism array. These stops are also polished optically flat. Respective actuators 58 move each prism element against either the top or bottom stop. Any of the prisms held against a given stop are aligned to each other with very high tolerance due to the optical precision in polishing the elongated prism element flat before cutting the slots.

Associated with each retroreflector is an actuator. This is not shown explicitly in Figs. 4A or 4B, but Fig. 4C shows actuator 58 explicitly. The particular type of actuator is not part of the invention, and many types of actuator mechanisms will be apparent to those skilled in the art. While Fig. 4C shows the actuator explicitly as a separate element (e.g., a piezoelectric transducer), the support plate can be made of a bimorph bender material and thus also function as the actuator. A piezoceramic bender, which is available from Piezo Systems, Inc., 186 Massachusetts Avenue, Cambridge, Massachusetts 02139, is a sandwich structure that bends when subjected to a voltage between electrodes on the two outer surfaces.

Movable-Mirror-Based Retroreflector Implementations

Fig. 5A shows schematically the operation of a retroreflector, designated 30c, that includes a pair of fixed mirrors 60a and 60b inclined with respect to one another (V-shaped, or open configuration as shown) and a rotatable mirror 61. The left portion of the figure shows the rotatable mirror positioned to direct the incoming beam to mirror 60a, while the right portion shows the rotatable mirror positioned to direct the incoming beam to mirror 60b. In each of the two orientations, the fixed mirror and the rotatable mirror define an included angle of 90° so as to provide a retroreflecting operation.

Fig. 5B shows schematically the operation of a retroreflector, designated 30d, that uses micromirrors. Fig. 5C is a top view. A pair of micromirror arrays 62 and 63 are mounted to the sloped faces of a V-block 64. A single micromirror 65 in micromirror array 62 and a row of micromirrors 66(1...M) in micromirror array 63 define

a single retroreflector. Micrometer arrays may conveniently be referred to as the input and output micromirror arrays, with the understanding the light paths are reversible. The left portion of the figure shows micromirror 65 in a first orientation so as to direct the incoming beam to micromirror 66(1), which is oriented 90° with respect to micromirror 65's first orientation to direct the beam back in a direction opposite to the incident direction. The right half of the figure shows micromirror 65 in a second orientation so as to direct the incident beam to micromirror 66(M). Thus, micromirror 65 is moved to select the output position of the beam, while micromirrors 66(1...M) are fixed during normal operation. Micromirror 65 and the row of micromirrors 66 (1...M) can be replicated and displaced in a direction perpendicular to the plane of the figure. While micromirror array 62 need only be one-dimensional, it may be convenient to provide additional micromirrors to provide additional flexibility.

It is preferred that the micromirror arrays are planar and that the V-groove have a dihedral angle of approximately 90° so that the two micromirror arrays face each other at 90°. This angle may be varied for a variety of purposes by a considerable amount, but an angle of 90° facilitates routing the incident beam with relatively small angular displacements of the micromirrors. For example, commercially available micromirror arrays (e.g., Texas Instruments) are capable of deflecting on the order of ±10°. The micromirror arrays may be made by known techniques within the field of micro-electro-mechanical systems (MEMS). In this implementation, the mirrors are formed as structures micromachined on the surface of a silicon chip. These mirrors are attached to pivot structures also micromachined on the surface of the chip. In some implementations, the micromirrors are selectably tilted about an suitably oriented axis using electrostatic attraction.

Fig. 5D shows schematically the operation of a retroreflector, designated 30e, that differs from the implementation shown in Fig. 5C in the use of a prism 69 rather than V-block 64. Corresponding reference numerals are used for like elements. As in the case of the V-groove, it is desired that the micromirror arrays, designated 62' and 63', face each other with an included angle of 90°. To this end, the prism preferably has faces with included angles of 90°, 45°, and 45°, and the micromirror arrays are mounted with the micromirrors facing the prism surfaces that define the right angle.

The micromirror arrays are preferably hermetically sealed from the external environment. This hermetic sealing may be accomplished by enclosing each micromirror array in a sealed cavity formed between the surface of the micromirror array

on its silicon chip and the surface of the prism. These silicon chips incorporating the micromirror arrays may be bonded around their periphery to the surface of the prism, with an adequate spacing between the mirrors and the surface of the prism. This sealed cavity may be formed to an appropriate dimension by providing a ridge around the periphery of the silicon chip. Alternatively, the function of this ridge may be performed by some other suitable peripheral sealing spacer bonded to both the periphery of the silicon chip and to the surface of the prism. If desired, each micromirror can be in its own cavity in the chip. The surfaces of the prism preferably have an anti-reflection coating.

The retroreflector implementations that comprise two arrays of tiltable micromirrors are currently preferred. Each micromirror in the input micromirror array receives light after the light's first encounter with the dispersive element, and directs the light to a mirror in the output micromirror array. By changing the angle of the mirror in the input array, the retroreflected light has a transverse displacement that causes it to encounter the dispersive element and exit the selected output port. As mentioned above, embodiments of the invention are reversible. The implementation with the V-block is generally preferred for embodiments where most of the optical path is in air, while the implementation with the prism is generally preferred for embodiments where most of the optical path is in glass. As an alternative to providing a separate prism or V-block, the input array mounting face and the output array mounting face may be formed as integral features of the router's optical housing.

The input micromirror array preferably has at least as many rows of micromirrors as there are input ports (if there are more than one), and as many columns of mirrors as there are wavelengths that are to be selectably directed toward the output micromirror array. Similarly, The output micromirror array preferably has at least as many rows of micromirrors as there are output ports, and as many columns of mirrors as there are wavelengths that are to be selectably directed to the output ports.

In a system with a magnification factor of one-to-one, the rows of micromirrors in the input array are parallel to each other and the component of the spacing from each other along an axis transverse to the incident beam corresponds to the spacing of the input ports. Similarly, the rows of micromirrors in the output array are parallel to each other and spaced from each other (transversely) by a spacing corresponding to that between the output ports. In a system with a different magnification, the spacing between the rows of mirrors would be adjusted accordingly.

Embodiments with Cylindrical Focusing Elements

Figs. 6A and 6B are schematic top and side views, respectively, of a wavelength router 70 according to an embodiment of the invention. This embodiment is an unfolded embodiment, and thus could be considered to correspond to the embodiment of Figs. 2A and 2B. This embodiment includes transmissive diffraction grating 25', as in the embodiment of Figs. 2A and 2B, but differs from that embodiment in that wavelength router 70 uses cylindrical lenses rather than spherical lenses, and tiltable mirrors rather than retroreflectors. The general functionality of wavelength router 70 is the same as the other embodiment, namely to accept light having a plurality of spectral bands at input port 12, and selectively direct subsets of the spectral bands to desired ones of a plurality of output ports 15(1 ... M).

The cylindrical lenses include a pair of lenses 72a and 72b, each having refractive power only in the plane of the top view (Fig. 6A), and a pair of lenses 75a and 75b each having refractive power only in the plane of the side view (Fig. 6B). As such, lenses 72a and 72b are drawn as rectangles in the plane of Fig. 6B, and lenses 75a and 75b are drawn as rectangles in the plane of Fig. 6A.

Light entering wavelength router 70 from input port 12 forms diverging beam 18, which includes the different spectral bands. Beam 18 encounters lens 72a, which collimates the light in one transverse dimension, but not the other, so that the beam has a transverse cross section that changes from circular to elliptical (i.e., the beam continues to expand in the plane of Fig. 6B, but not in the plane of Fig. 6A. The beam encounters lens 75a, grating 25', and lens 75b. Lenses 75a and 75b, together, collimate the light that is diverging in the plane of Fig. 6B so that the beam propagates with a constant elliptical cross section. Grating 25' disperses the light in the plane of Fig. 6A so that beams at different wavelengths are transmitted at different angles in the plane of Fig. 6A, but not in the plane of Fig. 6B.

The collimated beams encounter lens 72b, and are focused to respective lines. The focused beams encounter respective ones of plurality of tiltable mirrors 80(1 ... N), located near the focal plane. The beams are directed, diverging only in the plane of Fig. 6A, to lens 72b. Depending on the tilt angles of the respective mirrors, the beams are angularly displaced in the plane of Fig. 6B. The return beams undergo different transformations in the planes of Figs. 6A and 6B, as will now be described.

In the plane of Fig. 6A, the beams are collimated by lens 72b, and directed once more to grating 25' (in this plane, lenses 75b and 75a do not change the collimated

character of the beams). Grating 25', on this second encounter, removes the angular separation between the different beams, and directs the collimated beams back to lens 72a, which focuses the beams (only in the plane of Fig. 6A) at output ports 15(1 ... M). In Fig. 6A, the return beams are not shown separately, but rather have projections in the plane that coincide with the projection of the forward beam.

In the plane of Fig. 6B, the beams are focused by lenses 75a and 75b onto the output ports. However, due to the possible angular displacement of each beam by its respective mirror, the beams will be directed to one or another of output ports 15(1 ... M). In Fig. 5B, grating 25' and lenses 72b and 72a do not affect the direction of the beams, or whether the beams are diverging, collimated, or converging. The lenses 75a and 75b provide a Fourier relation in the plane of the side view, between mirrors 80(1 ... N) and output ports 15(1 ...M). This Fourier relation maps tilted wavefronts at the mirrors to displaced positions at the output ports.

In the specific implementation, input port 12, lens 72a, lens pair 75a/75b, lens 72b, and the tiltable mirrors are spaced at approximately equal intervals, with the focal length of the lens defined by lens pair 75a/75b being twice that of lenses 72a and 72b. This is not necessary, but is preferred. With these focal lengths and relative positions, lenses 72a and 72b define a 4f relay between input port 12 and the tiltable mirrors. Furthermore lens pair 75a/75b (treated as one lens), but encountered twice, defines a 4f relay between the input port and the output ports. The optical system is preferably telecentric.

Figs. 7A and 7B are schematic top and side views, respectively, of a wavelength router 70'-according to an embodiment of the invention. This embodiment is a folded version of the embodiment of Figs. 6A and 6B, and relates to that embodiment in a similar way to the way that the embodiment of Figs. 1A-1C is a folded version of the embodiment of Figs. 2A and 2B. Like the embodiment of Figs. 1A-1C, wavelength router 70' uses a reflective diffraction grating 25. In view of its folded nature, this embodiment uses single cylindrical lenses 72 and 75 corresponding to lens pairs 72a/72b and 75a/75b in the embodiment of Figs. 6A and 6B.

The operation is substantially the same as in the embodiment of Figs. 6A and 6B except for the folding of the optical path. In this embodiment, the light encounters each lens four times, twice between the input port and the tiltable mirrors, and twice on the way from the tiltable mirrors to the output ports. It should be noted that

diverging light encountering lens 75 is made less divergent after the first encounter and parallel (collimated) after the second encounter.

Embodiments with Combined Focusing/Dispersion Element

Figs. 8A and 8B are schematic top and side views, respectively, of a wavelength router 90 according to an embodiment of the invention. This corresponds generally to the wavelength router shown in Figs. 1A and 1B, except that the spherical focal power is incorporated in the grating itself. Thus optical power and dispersion are combined in a single element 95. This can be accomplished by ruling the grating on a curved surface, or by ruling curved grating lines on a flat surface. One popular alternative to the ruling engine for providing these grating lines is a holographic method in which photoresist is spun onto the grating substrate and exposed with the interference pattern from two diverging beams of light emanating from the intended source and focal points of the grating. The exposure light is at the midband wavelength or at an integer multiple of the midband wavelength. The exposed photoresist may be developed and used as is, or used as a barrier in an etching process.

Figs. 9A and 9B are schematic top and side views, respectively, of a wavelength router 100 according to an embodiment of the invention. This corresponds generally to the wavelength router shown in Figs. 7A and 7B, which use cylindrical lenses and tilting mirrors, except that the cylindrical focal power is incorporated in the grating ruling in a single element 105. The focal power in the dimension of the top view of Fig. 9A is twice that in the top view of Fig. 9B. The holographic version of this grating may be constructed by exposing photoresist with the interference pattern from one diverging beam and one line source of light emanating from the intended source and focal line of the grating.

Prism Embodiment

Figs. 10A and 10B are schematic top and side views, respectively, of a wavelength router 10''' which uses a prism 107 instead of a grating as shown in the embodiments described above. The embodiment of Figs. 10A and 10B correspond to the embodiment of Figs. 2A and 2B, and corresponding reference numerals are used.

Control Electronics

Fig. 11 shows a wavelength router system 110 including a wavelength router 112 and representative control electronics. Wavelength router 112 can be

configured according to any of the above described embodiments, and would be considered to include routing elements such as the various retroreflectors and tilting mirrors, a dispersive element such as a diffraction grating or prism, and actuators to move the routing elements (at least in dynamic embodiments). The wavelength router is shown as having one input port 12 and two output ports 15(1) and 15(2), using the reference numerals corresponding to Fig. 1A. For definiteness, the wavelength router is shown as being able to handle 80 wavelength channels. In the nomenclature of the above description of the wavelength router, M=2 and N=80. The operation is to provide desired disjoint subsets λ(out_1) and λ(out_2) of the wavelengths at the two output ports. Each subset can, under some circumstances, contain all or none of the input wavelengths.

The control electronics includes actuator control circuitry 113, which provides suitable control signals to the actuators in wavelength router 110. The actuator control circuitry is controlled by a controller 114, and could be viewed as an interface between the controller and the wavelength router. The actuator control electronics may include digital switches, power drivers, and digital-to-analog converters (DACs). The controller, which determines the state of the multi-state elements, may be a microprocessor, an embedded microcontroller, and ASIC, or any logic suitable for controlling the actuator control circuitry. The interface between controller 114 and actuator control circuitry 113 can take several common forms, such as a parallel set of control lines or a microprocessor-compatible address/data/control bus.

In some cases, it may be possible to dispense with separate actuator control circuitry. For example, the wavelength router may have interface circuitry that allows the wavelength router to respond to direct commands from controller 114. There is, as a matter of design choice, an inevitable division of labor between wavelength router 110 and the control electronics. The present invention is not limited to any particular apportionment of functionality with respect to the control of the wavelength router actuators. In a current implementation, the wavelength router does not contain any control electronics at all other than simple drivers (actuator electronics). Rather, all of the intelligence and control circuitry is contained within the control electronics.

Controller 114 preferably also communicates with other computers in the network environment using standard or proprietary interfaces and protocols. This is shown schematically as a network management interface 115. These other computers are typically executing network management applications.

Band Shape and Resolution Issues

The physical positions in the plane of the retroreflector array correspond to frequencies with a scale factor determined by the grating dispersion and the lens focal length. The grating equation is $Nm\lambda = \sin\alpha \pm \sin\beta$ where N is the grating groove frequency, m is the diffraction order, λ is the optical wavelength, β is the incident optical angle, and α is the diffraction angle. The lens maps the diffraction angle to position, x, at its back focal length, f, according to the equation $x = f\sin\alpha$. With the mirrors in the back focal plane of the lens, we have a linear relation between position in the mirror plane and the wavelength, $\lambda Nm = x/f \pm \sin\beta$. For a small wavelength a change in frequency is proportional to a change in wavelength. This gives us a scale factor between position and frequency of $\Delta x/\Delta\nu = fNm\lambda^2/c$. The position scale in the mirror plane is thus a frequency scale with this proportionality constant.

Fig. 11A shows a preferred substantially trapezoidal band shape. In short, this is achieved by making the resolution of the grating finer than the size of the mirrors sampling the frequency domain. For an extremely large ratio of the grating spot size to the mirror size, the band pass response for each channel would merely be the rectangular response given by the mirror position in the perfectly resolved frequency plane of the grating. For finite grating resolution, the band pass response is a convolution of the spot determined by the diffraction from the grating with the rectangular sampling of the mirror. The result of such a convolution is depicted in Fig. 11A for a grating with a Gaussian like spot with finer resolution in the mirror plane than the mirror size. It is preferred for embodiments of the invention to provide a large ratio of mirror width to grating resolution because the resultant trapeziodal band shapes have a large usable flat top region as compared to the size of the unusable portion between bands, and this makes the utilization of the spectrum more efficient.

Fig. 11B also shows a differential path length in the optical beam at the angle of diffraction from the grating. This differential path length determines the frequency resolution of the grating. Within an order unity coefficient, determined by the transverse shape of the optical beam, the frequency resolution is the speed of light divided by this differential path length. Specific embodiments have optical bands separated by the ITU spacing of 100 GHz or finer. Consequently, it is preferred that the grating resolution be 10 GHz or finer to allow for a large flat band shape between channels, which will permit low-loss transmission of OC-768 data on 100 GHz channel spacings, or

OC-192 data on 25 GHz spacings. This 10 GHz or finer grating resolution requires a differential path length of 3 cm or longer. In the folded geometry of Fig. 1A, this 3 cm is the round trip differential path length, or a one-way differential of 1.5 cm.

Fig. 12C shows a router 10''' where the differential path length is in a glass wedge 117. This embodiment corresponds to that of Fig. 1A. It is highly preferred that the center wavelength for these wavelength routers be stable with temperature. The 3-cm differential path length corresponds to approximately 20,000 waves at the preferred center wavelength of 1550 nm. The preferred design has a change in the differential path length of less than one part in 20,000 over the preferred temperature range of at least 50°C. This requires that the differential path length change by less than one part in one million per degree Celsius. One way to achieve this temperature stability is to make the portion of the wavelength router containing the differential path length, wedge 117 shown in Fig. 12C, out of a glass that has thermal coefficient of less than one part in one million.

Polarization Considerations

The efficiency of the diffraction grating depends on the polarization state of the incident light. The electric field **E** of an arbitrarily polarized incident optical signal may be written as a superposition of two electric fields linearly polarized along two orthogonal axes $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$:

$$\mathbf{E} = E_x\hat{\mathbf{x}} + E_y\hat{\mathbf{y}}.$$

where $\hat{\mathbf{x}}$ is the direction of the grating dispersion and $\hat{\mathbf{y}}$ is orthogonal to the dispersion direction. The intensity I_0 of the incident signal is defined by the strength of the electric field along the orthogonal directions:

$$I_0 = |E_x|^2 + |E_y|^2.$$

The efficiency is governed by independent efficiency coefficients ε in the orthogonal polarization directions such that the electric field $\mathbf{E}'$ of the signal reflected by the grating is

$$\mathbf{E}' = -\sqrt{\varepsilon_x}E_x\hat{\mathbf{x}} - \sqrt{\varepsilon_y}E_y\hat{\mathbf{y}},$$

with total intensity

$$I' = \varepsilon_x|E_x|^2 + \varepsilon_y|E_y|^2.$$

It is thus evident that the intensity of a signal linearly polarized along one of the two orthogonal axes is reflected by the diffraction grating with an intensity dependent only on the efficiency coefficient for that direction:

$$I^x = \varepsilon_x |E_x|^2$$
$$I^y = \varepsilon_y |E_y|^2.$$

For most diffraction gratings, $\varepsilon_x \neq \varepsilon_y$, so there may be large variability in the overall efficiency as a function of the polarization state of the incident signal.

In embodiments of the invention, this variability is reduced or eliminated by imposing a wave delay along one polarization component. This may be achieved by using a wave plate, which is constructed asymmetrically so that different indices of refraction are achieved in two orthogonal directions. Thus, when the incident optical signal passes through the wave plate, one component of the electric field is delayed relative to the other. Typically, wave plates are constructed to impose phase differences of π ("half-wave plate") or $\pi/2$ ("quarter-wave plate"). For use in embodiments of the invention, a quarter-wave plate (or a wave plate which provides an approximately quarter-wave delay) is used.

Using the result provided above for the effect of a reflection from the diffraction grating, the electric field after two reflections from the reflective diffraction grating is seen to be

$$\mathbf{E}^0_{fin} = \varepsilon_x E_x \hat{\mathbf{x}} + \varepsilon_y E_y \hat{\mathbf{y}},$$

and has total intensity

$$I^0_{fin} = \varepsilon_x^2 |E_x|^2 + \varepsilon_y^2 |E_y|^2.$$

The potentially large variability in overall system efficiency is eliminated by including a quarter-wave plate between the retroreflectors and the lens (20 in Figs. 1A-1C or 20b in Figs. 2A and 2B). With such positioning, each subbeam passes through the quarter-wave plate twice, before it is retroreflected (i.e., immediately before step (5)) and after it is retroreflected (i.e., immediately after step (5)). Just before its first pass through the quarter-wave plate (i.e. after one reflection from the diffraction grating), the electric field is

$$\mathbf{E}' = -\sqrt{\varepsilon_x} E_x \hat{\mathbf{x}} - \sqrt{\varepsilon_y} E_y \hat{\mathbf{y}}.$$

After passing through the quarter-wave plate, reflecting off two surfaces in the retroreflector, and passing through the quarter-wave plate a second time, the electric field is

$$\mathbf{E}'' = \sqrt{\varepsilon_y} E_y \hat{\mathbf{x}} - \sqrt{\varepsilon_x} E_x \hat{\mathbf{y}}.$$

Two passes through the quarter-wave plate rotate the x component of the electric field to y polarization and rotate the y component to x polarization. Thus, after reflecting off the reflective grating G_r a second time, the electric field is

$$\mathbf{E}_{fin} = -\sqrt{\varepsilon_x}\sqrt{\varepsilon_y} E_y \hat{\mathbf{x}} + \sqrt{\varepsilon_x}\sqrt{\varepsilon_y} E_x \hat{\mathbf{y}},$$

having total intensity

$$I_{fin} = \varepsilon_x \varepsilon_y |E_x|^2 + \varepsilon_x \varepsilon_y |E_y|^2 \equiv \varepsilon_x \varepsilon_y I_0.$$

Thus, the electric field and its intensity are independent of the state of polarization of the incident wave, thereby eliminating polarization-dependent loss.

Similarly a magnetooptic retarder designed to rotate linear polarization by 45 degrees with each pass rotates the $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ polarizations into $\hat{\mathbf{y}}$ and $\hat{\mathbf{x}}$ polarizations, respectively, after two passes. This interchange of polarizations between the first and second reflection from the grating eliminates the polarization dependence of the overall grating efficiency.

The quarter wave plate or magnetooptic retarder may be placed anywhere in the optical system of Fig. 1A, since any placement accomplishes a double pass between the first and second reflection from the grating. Placement of the quarter wave plate or magnetooptic retarder between the lens and the grating allows the component to operate where the optical beam is collimated. This may allow the system to be designed for lower optical aberrations due to this element. This may also improve the performance of the wave plate.

System Applications

The following discussion describes a number of systems using multiple wavelength routers. Each of the wavelength routers is shown as having a single input port and two output ports, and for definiteness as being able to handle 80 wavelength channels. In the nomenclature of the above description of the wavelength router, M=2 and N=80. The wavelength routers are designated with suffixed reference numerals 110, and will typically have control electronics such as shown in Fig. 11. As a pure optical

schematic, however, wavelength routers 112 without associated control circuitry could be substituted.

The wavelength routers can be fabricated according to any of the above described embodiments of the invention, or could be fabricated in other ways so long as they provided the functionality of wavelength routing as described herein. In general, as noted above, the light paths within the wavelength routers of the above embodiments of the invention are reversible.

Optical Add-Drop Multiplexer (OADM)

Fig. 13 is a schematic showing an optical add-drop multiplexer (OADM) 120 formed by combining a pair of wavelength routers 110a and 110b in a back-to-back configuration. The general functionality of the OADM is to receive a set of wavelength channels at an input port 132, pass a subset (including all or none) of the wavelengths (the through wavelengths) to an output port 133, divert (drop) those wavelengths not passed from the through path to a drop port 135, receive some or all of the dropped wavelengths (presumably carrying new information) at an add port 137, and combine the added wavelengths with the through wavelengths so that the through and the added wavelengths exit output port 133.

In the back-to-back configuration, input port 132 of OADM 120 is what would be considered the input port of wavelength router 110a while output port 133 of OADM 120 is what would be considered the input port of wavelength router 110b. The through path is effected by coupling the first output ports of the wavelength routers. Drop port 135 and add port 137 are what would be considered the second output ports of the wavelength routers. The drop and add ports could be coupled to sending and/or receiving terminal equipment or to one or more other networks. Depending on the application, only one of the add and drop functions may be necessary.

Wavelength-Selective Cross-Connect (WSXC)

Fig. 14 is a schematic showing a wavelength-selective cross-connect (WSXC) 140 formed by combining four wavelength routers 110a-110d in a paired back-to-back configuration. The general functionality of the WSXC is to receive first and second sets of wavelength channels at first and second input ports 142 and 142', and pass selected subsets of the wavelengths on respective through paths to first and second output ports 143 and 143', while exchanging those wavelengths not passed on the through paths.

Thus the exchanged wavelengths from input port 142 emerge from exchange output ports 145 and 145' of wavelength routers 110a and 110c and are communicated to exchange input ports 147' and 147 of wavelength routers 110d and 110b, respectively. The exchanged wavelengths entering the exchange input ports are combined for output with the wavelengths on the through paths to emerge from output ports 143 and 143'. Again, as in the case of OADM described above, the output ports of WSXC 140 are what would be considered input ports of wavelength routers 110b and 110d.

OMSSPRing Protection Switching

Fig. 15 is a schematic showing a switching configuration 150 to provide protection switching in an optical multiplexed section shared protection ring (OMSSPRing) optical network. Configuration 150 is formed by combining four wavelength routers 110a-110d in a paired back-to-back configuration along the lines of WSXC 140 described above. This configuration differs from the WSXC in two main respects. First, in the WSXC, both the upper and lower pairs of wavelength routers operate with light traveling in the same direction, while in the switching configuration, the upper and lower pairs handle traffic in opposite directions, arbitrarily denoted "East" and "West." Second, instead of the exchange ports in the WSXC, the switching configuration provides loopback paths 152 and 155. Thus, it is possible to divert a subset of the wavelengths incoming to wavelength router 110a on the East fiber and direct them back onto the West fiber outgoing from wavelength router 110c. Similarly, those wavelengths (or perhaps a different set) that are incoming to wavelength router 110d on the West fiber are diverted and directed back onto the East fiber outgoing from wavelength router 110b.

The capability of diverting a subset of the wavelengths from the East fiber back onto the West fiber makes it possible to protect the ring from fault modes that affect a subset of the wavelengths, such as laser failures and OADM errors.

Drop-and-Repeat OADM

A drop-and-repeat OADM (sometimes referred to as a "broadcast mode" OADM) has the functionality of the OADM discussed above, but further has the capability of continuing transmission of the dropped wavelengths on the output port. The discussions below describe embodiments based on the OADM of Fig. 13 and the WSXC

of Fig. 14, but other forms of OADM or WSXC could be used. Corresponding elements of the OADM and WSXC are denoted with the same reference numerals.

Fig. 16 is a schematic showing a drop-and-repeat OADM 160 based on the OADM of Fig. 13, which has input and output ports 132 and 133, and drop and add ports 135 and 137. Drop-and-repeat OADM 160 has the same input and output ports, but has additional elements interposed between the OADM's drop and add ports 135 and 137, and provides other ports, designated 135' and 137', that are the functional drop and add ports of the drop-and-repeat OADM.

The additional elements include an optional optical amplifier 162, a 50% tap coupler (or other splitter) 165 having an input port and first and second output ports, and an optical coupler or combiner 167 having first and second input ports and an output port. The optical amplifier receives the light from drop port 135 and the optionally amplified light is split at tap coupler 165. The light from the second output port of the tap coupler constitutes the dropped wavelengths, whereupon the second output port defines functional drop port 135'. Thus this output light corresponds to the light from drop port 135 in Fig. 13. These same wavelengths, as output from the first output port of the tap coupler, are referred to as the "repeat wavelengths," and are communicated to the first input port of optical coupler 167.

Wavelengths to be added to the network traffic, referred to as the "add wavelengths," are communicated to the second input port of optical coupler 167, which port defines functional add port 137'. These wavelengths are combined with the repeat wavelengths, and communicated to add port 137 of the OADM building block. The through wavelengths, the repeat wavelengths, and the add wavelengths are then output from output port 133.

Fig. 17 is a schematic showing a drop-and-repeat OADM 170 based on the WSXC of Fig. 14, which has first and second input ports 142 and 142', and first and second output ports 143 and 143'. First input port 142 and first output port 143 function as the input and output ports of drop-and-repeat OADM 160', but other elements are interposed between second output port 143' and second input port 142'. The other elements provide other ports, designated 172 and 175, that are the functional drop and add ports of the drop-and-repeat OADM.

The interposed elements are the same as in the case of drop-and-repeat OADM 160, and corresponding reference numerals are used. As above, optical amplifier 162 receives the light from second output port 143' and the optionally amplified light is

split at tap coupler 165. The light from the second output port of the tap coupler constitutes the dropped wavelengths, whereupon the second output port defines functional drop port 172. Thus this output light corresponds to the light from drop port 135 in Fig. 13. The repeat wavelengths are communicated to the first input port of optical coupler 167, and are combined with the add wavelengths, which are communicated to the second input port of optical coupler 167, which port defines functional add port 175. These wavelengths are combined with the repeat wavelengths, and communicated to input port 142' of the WSXC building block. The through wavelengths, the repeat wavelengths, and the add wavelengths are then output from first output port 143.

Conclusion

While the above is a complete description of specific embodiments of the invention, various modifications, alternative constructions, and equivalents may be used. For example, while the dynamically configurable routing elements (retroreflectors and the like) were described as including movable elements, switching could also be effected by using electro-optic components. For example, an electro-optic Fabry-Perot reflector could be used.

Therefore, the above description should not be taken as limiting the scope of the invention as defined by the claims.

WHAT IS CLAIMED IS:

1. A wavelength router for receiving, at an input port, light having a plurality of spectral bands and directing subsets of said spectral bands to respective ones of a plurality of output ports, the wavelength router comprising:

a free-space optical train disposed between the input ports and said output ports providing optical paths for routing the spectral bands, the optical train including a dispersive element disposed to intercept light traveling from the input port, said optical train being configured so that light encounters said dispersive element twice before reaching any of the output ports; and

a routing mechanism having at least one dynamically configurable routing element to direct a given spectral band to different output ports, depending on a state of said dynamically configurable element.

2. The wavelength router of claim 1 wherein said input port is located at the end of an input fiber.

3. The wavelength router of claim 1 wherein said output ports are located at respective ends of a plurality of output fibers.

4. The wavelength router of claim 1 wherein said routing mechanism has a configuration that directs at least two spectral bands to a single output port.

5. The wavelength router of claim 1 wherein said routing mechanism has a configuration that results in at least one output port receiving no spectral bands.

6. The wavelength router of claim 1 wherein the number of spectral bands is greater than the number of output ports, and the number of output ports is greater than 2.

7. The wavelength router of claim 1 wherein said routing mechanism includes a plurality of reflecting elements, each associated with a respective one of the spectral bands.

8. The wavelength router of claim 1 wherein said dynamically configurable element has a translational degree of freedom.

9. The wavelength router of claim 1 wherein said dynamically configurable element has a rotational degree of freedom.

10. The wavelength router of claim 1 wherein said dynamically configurable element includes mirrors made from micro-electro-mechanical system (MEMS) elements.

11. The wavelength router of claim 1 wherein:

said dispersion element is a grating; and

said optical train includes optical power incorporated into said grating.

12. The wavelength router of claim 1 wherein:

said optical train includes a lens;

said dispersive element is a reflection grating;

said routing mechanism includes a plurality of dynamically configurable elements;

light coming from said input port is collimated by said lens and is reflected from said reflection grating as a plurality of angularly separated beams corresponding to said spectral bands;

said angularly separated beams are focused by said lens on respective ones of said dynamically configurable elements; and

each given dynamically configurable element has a plurality of states, each adapted to direct that dynamically configurable element's respective angularly separated beam along a desired one of a plurality of paths such that light leaving that dynamically configurable element is again collimated by said lens, reflected by said reflection grating, and again focused by said lens on one of said output ports corresponding to the desired one of said plurality of paths.

13. The wavelength router of claim 1 wherein said dispersive element is a grating having a resolution significantly less than a separation between spectral bands.

14. The wavelength router of claim 13 wherein the resolution is achieved by a differential path length greater than about 3 cm.

15. A wavelength add-drop multiplexer comprising:

first and second wavelength routers according to claim 1, connected in opposite directions with a first subset of the first wavelength router's output ports in optical communication with a corresponding first subset of the second wavelength router's output ports, said first wavelength router's input port being in optical communication with an upstream fiber, said second wavelength router's input port being in optical communication with downstream fiber, and respective second subsets of said first and second wavelength routers' output ports being in communication with network terminal equipment for receiving light from one of the second subsets of output ports and communicating light onto the other of the second subsets of output ports.

16. A wavelength router for receiving light having a first number, N, of spectral bands at an input port and directing subsets of said N spectral bands to respective ones of a second number, M, of output ports, the wavelength router comprising:

a free-space optical train disposed between the input ports and said output ports providing optical paths for routing the spectral bands, the optical train including a dispersive element disposed to intercept light traveling from the input port, said optical train being configured so that light encounters said grating element twice before reaching any of the output ports; and

wherein M is greater than 2.

17. The wavelength router of claim 16 wherein said dispersive element is a reflection grating, and the optical train includes:

a lens disposed to intercept light from the input port, collimate the intercepted light, direct the collimated light toward said reflection grating, intercept light reflected from the reflection grating, focus the light, and direct the focused light along a path, with each spectral band being focused at a different point; and

a plurality of N reflecting elements disposed to intercept respective focused spectral bands and direct the same so as to encounter said lens, said reflection grating, said lens, and respective output ports.

18. The wavelength router of claim 16 wherein said dispersive element is a transmission grating, and the optical train includes:

a lens disposed between said transmission grating and the input port; and

a plurality of N reflecting elements on a side of said transmission grating that is remote from said input port so as to cause light passing through said grating and falling on said reflecting elements to pass through said transmission grating, said lens and said the output ports.

19. The wavelength router of claim 16 wherein said dispersive element is a reflection grating, and the optical train includes:

a curved reflector disposed to intercept light from the input port, collimate the intercepted light, direct the collimated light toward said reflection grating, intercept light reflected from the reflection grating, focus the light, and direct the focused light along a path, with each spectral band being focused at a different point; and

a plurality of N reflecting elements disposed to intercept respective focused spectral bands and direct the same so as to encounter said curved reflector, said reflection grating, said curved reflector, and respective output ports.

20. The wavelength router of claim 16 wherein said dispersive element is a prism.

21. The wavelength router of claim 16 wherein said optical path includes mirrors made from micro-electro-mechanical system (MEMS) elements.

22. A wavelength router for receiving light having a first number, N, of spectral bands at an input port and directing subsets of said N spectral bands to respective ones of a second number, M, of output ports, the wavelength router comprising:

a first cylindrical lens for collimating light emanating from the input port in a first transverse dimension;

a second cylindrical lens for collimating the light in a second transverse dimension that is orthogonal to said first transverse dimension;

a transmissive dispersive element for dispersing the light in said first transverse dimension in a particular sense;

a third cylindrical lens for focusing the light in the first transverse dimension;

a plurality of N tiltable mirrors in the focal plane of said third cylindrical lens, each intercepting a respective spectral band and directing that spectral band back toward said third cylindrical lens; and

a plurality of actuators, each coupled to a respective mirror to effect selective tilting of the light path of the respective spectral band;

wherein each spectral band is collimated in the first transverse dimension by said third cylindrical lens, dispersed in the first transverse dimension by the grating in a sense opposite the particular sense, focused in the second transverse dimension by said second cylindrical lens and focused in the first transverse dimension by said first cylindrical lens, whereupon each spectral band is brought to a focus in both the first and second transverse dimensions at a respective position determined by the respective tiltable mirror.

23. The wavelength router of claim 22, and further comprising an array of output fibers positioned to receive light from said return path, whose positions correspond to the tilts of said plurality of tiltable mirrors in a Fourier relationship through said second cylindrical lens.

24. The wavelength router of claim 22 wherein said mirrors are made from micro-electro-mechanical system (MEMS) elements.

25. A wavelength router for receiving light having a first number, N, of spectral bands at an input port and directing subsets of said N spectral bands to respective ones of a second number, M, of output ports, the wavelength router comprising:

a first spherical lens for collimating light emanating from the input port;

a transmissive dispersive element for dispersing the light in a first transverse dimension in a particular sense to spatially separate the spectral bands;

a second spherical lens for focusing the light traveling from said dispersive element; and

a plurality of retroreflectors in the focal plane of said second spherical lens, each retroreflector intercepting a respective spectral band and directing that spectral band back toward said second spherical lens with a transverse displacement in a second transverse dimension that is orthogonal to the first transverse dimension, said transverse displacement depending on a state of that retroreflector;

wherein each spectral band is collimated by said second spherical lens, dispersed in the first transverse dimension by the grating in a sense opposite the particular sense, focused by said first spherical lens, whereupon each spectral band is brought to a focus at a respective position determined by the respective retroreflector.

26. A wavelength router for receiving light having a first number, N, of spectral bands at an input port and directing subsets of said N spectral bands to respective ones of a second number, M, of output ports, the wavelength router comprising:

an optical element with positive optical power disposed to collimate light emanating from the input port;

a reflective dispersive element for dispersing the light traveling from said optical element in a first transverse dimension in a particular sense to spatially separate the spectral bands, said dispersive element directing the spectral bands back to said optical element, which focuses the light traveling from said dispersive element; and

a plurality of retroreflectors in the focal plane of said optical element, each retroreflector intercepting a respective spectral band and directing that spectral band back toward said optical element with a transverse displacement in a second transverse dimension that is orthogonal to the first transverse dimension, said transverse displacement depending on a state of that retroreflector;

wherein each spectral band is collimated by said optical element, dispersed in the first transverse dimension by said dispersive element in a sense opposite the particular sense, focused by said optical element, whereupon each spectral band is brought to a focus at a respective position determined by the respective retroreflector.

27. The wavelength router of claim 26 wherein said optical element is a spherical lens.

28. The wavelength router of claim 26 wherein said optical element is a concave reflector.

29. The wavelength router of claim 26 wherein:

each retroreflector includes a rooftop prism; and

the state of that retroreflector is defined by a transverse position of that retroreflector's rooftop prism.

30. The wavelength router of claim 26 wherein:

each retroreflector includes a rooftop prism and a relatively movable associated body of transparent material configured for optical contact with that retroreflector's rooftop prism; and

the state of that retroreflector is defined at least in part by whether that retroreflector's rooftop prism is in optical contact with its associated body.

31. A configurable retroreflector array comprising:

a support element having first and second mounting surfaces lying in planes defining an angle therebetween of approximately 90°.

first and second MEMS micromirror arrays disposed on respective first and second substrates, mounted to said first and second mounting surfaces of said support element;

a given micromirror in said first array being associated with a plurality of M micromirrors in said second array; and

an actuator coupled to each given micromirror in said first array to provide M discrete orientations of said given micromirror, each orientation directing light along an incident direction toward a different micromirror in said second array;

said plurality of M micromirrors in said second array having respective orientations such that each respective orientation is substantially 90° to the orientation of the given mirror in said first array when the given mirror is oriented to direct light to that micromirror in said second array.

32. The configurable retroreflector array of claim 31 wherein:

said support element is a V-block having support surfaces facing toward each other; and

said first and second arrays are mounted with said first and second substrates disposed between the micromirrors in the arrays and said first and second mounting surfaces.

33. The configurable retroreflector array of claim 31 wherein:

said support element is a prism having support surfaces facing away from each other; and

said first and second arrays are mounted with the micromirrors in the arrays disposed between said first and second substrates and said first and second mounting surfaces.

34. The configurable retroreflector array of claim 31 wherein the micromirrors are limited to deflections on the order of ±10°.

35. A dynamically configurable retroreflector comprising:

first and second flat mirrors, fixed at a particular included angle with respect to one another, said first and second flat mirrors defining an intersection axis;

a third flat mirror mounted for rotation about a rotation axis parallel to said intersection axis; and

an actuator coupled to said third flat mirror configured to provide first and second angular positions about said rotation axis, said first angular position being such to define an included angle of approximately 90° between said first and third flat mirrors, said second angular position being such to define an included angle of approximately 90° between said second and third flat mirrors.

36. A method of making an array of rooftop prisms, the method comprising:

providing an elongate prism element;

providing a pair of elongate stop elements that have surfaces possessing a desired degree of flatness;

optically polishing surfaces of the elongate prism element to a desired degree of flatness;

subjecting the elongate prism element, thus optically polished, to a set of operations that provide the plurality of rooftop prisms that make up the array; and

providing respective positioning elements to the array of rooftop prisms for movement between the pair of elongate stop elements.

37. The method of claim 36 wherein:

the elongate prism element is a unitary component; and

the set of operations includes physically cutting the elongate prism element into individual prisms.

38. The method of claim 36 wherein:

the elongate prism element is a bonded component of individual prisms; and

the set of operations includes breaking the bonds between individual prisms.

39. An optical add-drop multiplexer (OADM) comprising:

first and second wavelength routers, each having a port, referred to as an input port, and a plurality of additional ports, referred to as output ports, including at least first and second output ports, each wavelength router configured to receive light having a plurality of spectral bands at that wavelength router's input port and direct selected subsets of said spectral bands to respective ones of said wavelength router's output ports;

said first and second wavelength routers being connected in opposite directions with a first subset of said first wavelength router's output ports in optical communication with a corresponding first subset of said second wavelength router's output ports, each of said wavelength routers' first subset of output ports being less than that wavelength router's plurality of output ports, whereby each of said wavelength routers has a second subset of output ports;

such that

said first wavelength router's input port functions as an input port for the OADM,

said second wavelength router's input port functions as an output port for the OADM,

said first wavelength router's second subset of output ports provides a drop port functionality for the OADM, and

said second wavelength router's second subset of output ports provides an add port functionality for the OADM.

40. The OADM of claim 39 wherein each wavelength router has only first and second output ports, which define said first and second subsets of output ports for that wavelength router.

41. A drop-and-repeat OADM comprising:

the OADM of claim 39;

a splitting element having an input port and first and second output ports;

a combining element having first and second input ports and an output port; and

a set of optical paths providing optical communication between said OADM's drop port and said splitting element's input port, between said splitting

element's first output port and said combining element's first input port, and between said combining element's output port and said OADM's add port.

42. The drop-and-repeat OADM of claim 41, and further comprising an optical amplifier disposed in said optical path between said OADM's drop port and said splitting element's input port.

43. A wavelength-selective cross-connect (WSXC) comprising

first, second, third, and fourth wavelength routers, each having a port, referred to as an input port, and a plurality of additional ports, referred to as output ports, including at least first and second output ports, each wavelength router configured to receive light having a plurality of spectral bands at that wavelength router's input port and direct selected subsets of said spectral bands to respective ones of said wavelength router's output ports;

said first and second wavelength routers being connected in opposite directions with said first wavelength router's first output port in optical communication with said second wavelength router's first output port;

said third and fourth wavelength routers being connected in opposite directions with said third wavelength router's first output port in optical communication with said fourth wavelength router's first output port;

said first wavelength router's second output port being in optical communication with said fourth wavelength router's second output port;

said third wavelength router's second output port being in optical communication with said second wavelength router's second output port;

such that

said first and second wavelength routers' input ports function as first and second input ports for the WSXC,

said third and fourth wavelength routers' input ports functions as first and second output ports for the WSXC,

said optical communication between said first output ports of said first and second wavelength routers and said optical communication between said first output ports of said third and fourth wavelength routers provide through paths for the WSXC, and

said optical communication between said second output ports of said first and fourth wavelength routers and said optical communication between said second output ports of said third and second wavelength routers provide exchange paths for the WSXC.

44. A drop-and-repeat OADM comprising:

the WSXC of claim 43;

a splitting element having an input port and first and second output ports;

a combining element having first and second input ports and an output port; and

a set of optical paths providing optical communication between said WSXC's second output port and said splitting element's input port, between said splitting element's first output port and said combining element's first input port, and between said combining element's output port and said WSXC's second input port.

45. The drop-and-repeat OADM of claim 44, and further comprising an optical amplifier disposed in said optical path between said WSXC's second output port and said splitting element's input port.

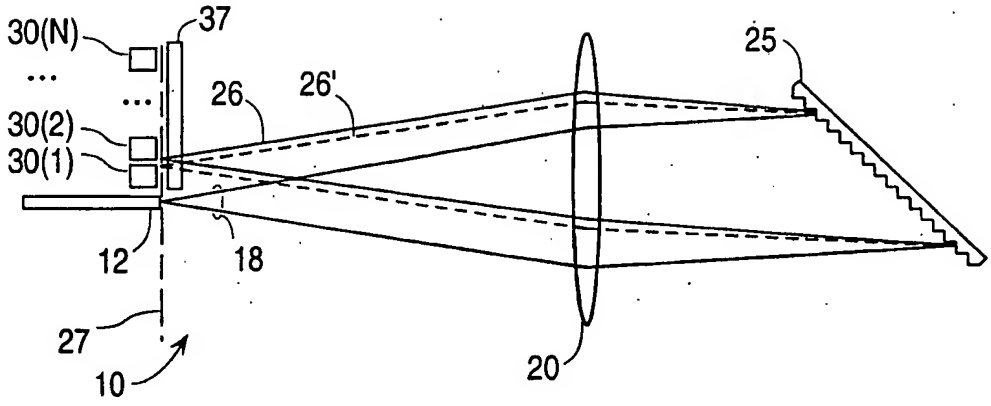

FIG. 1A

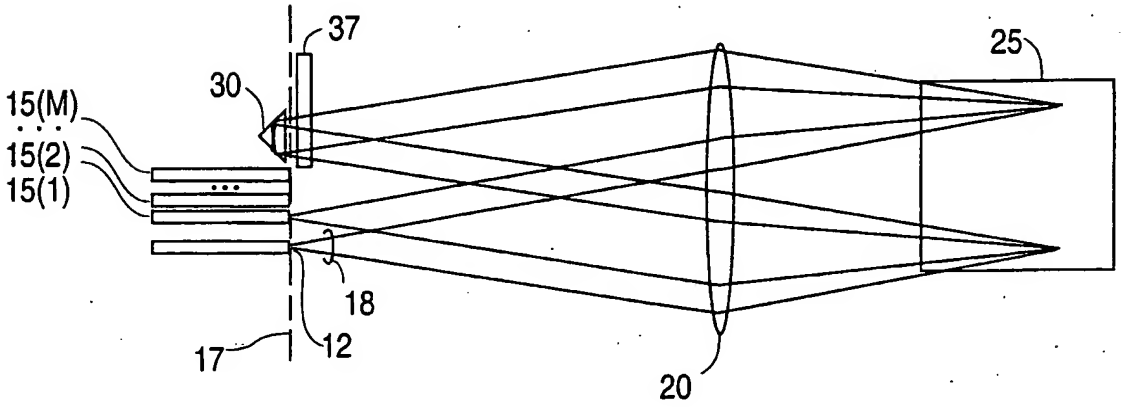

FIG. 1B

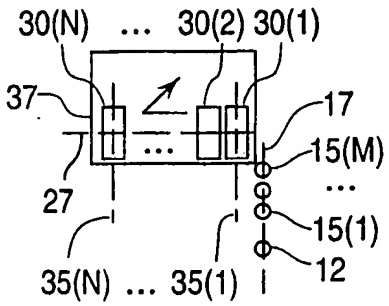

FIG. 1C

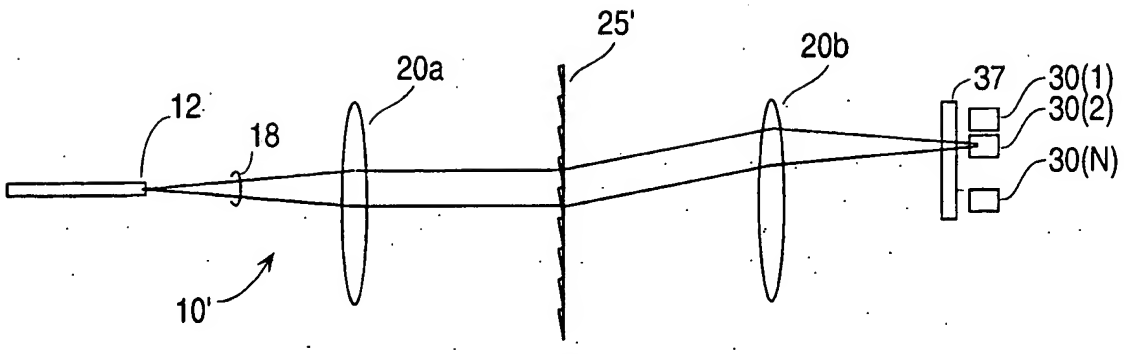

FIG. 2A

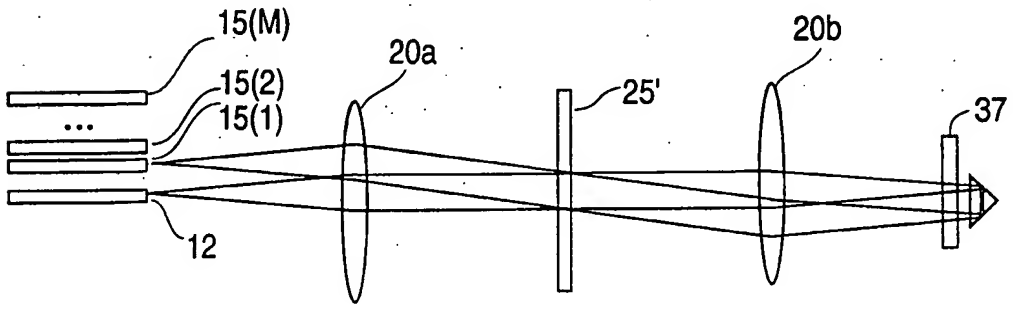

FIG. 2B

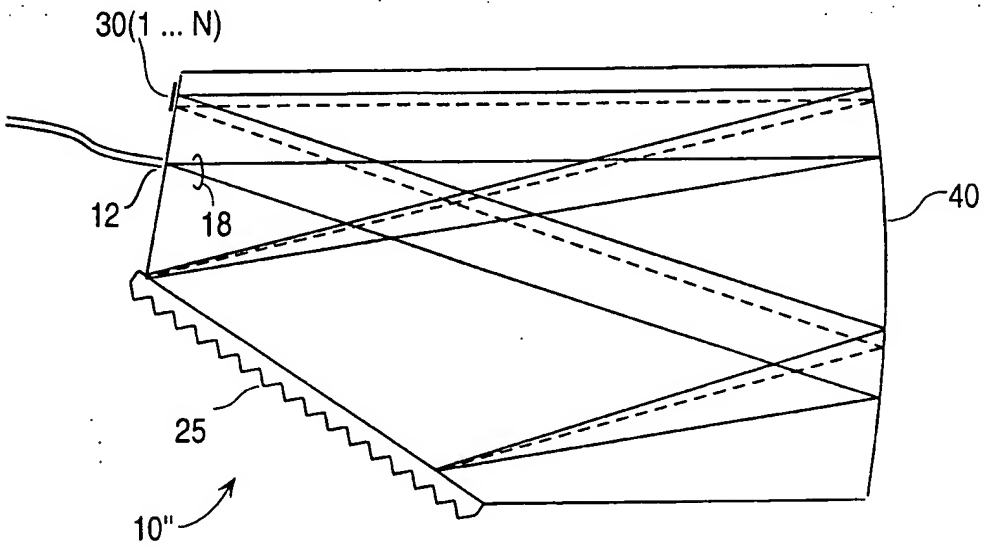

FIG. 3

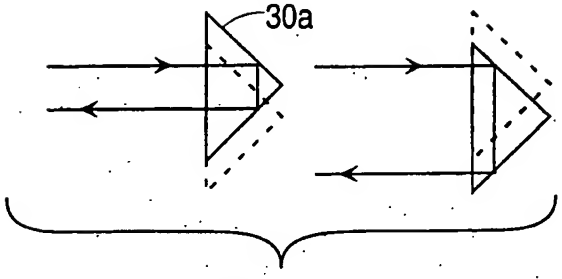

FIG. 4A

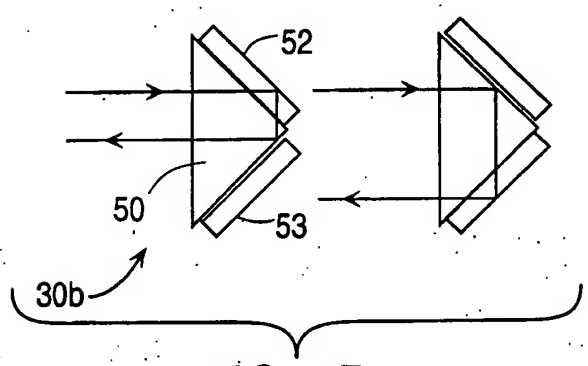

FIG. 4B

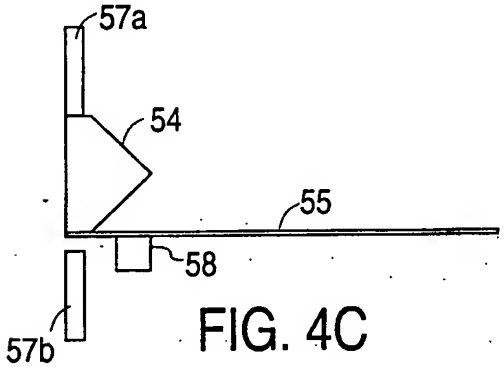

FIG. 4C

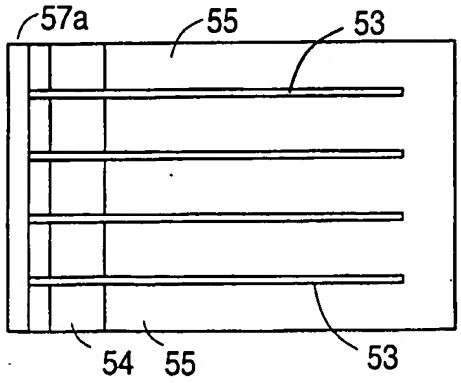

FIG. 4D

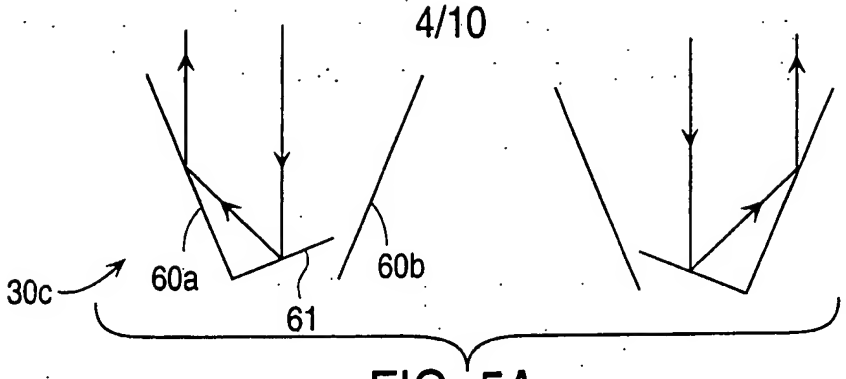

FIG. 5A

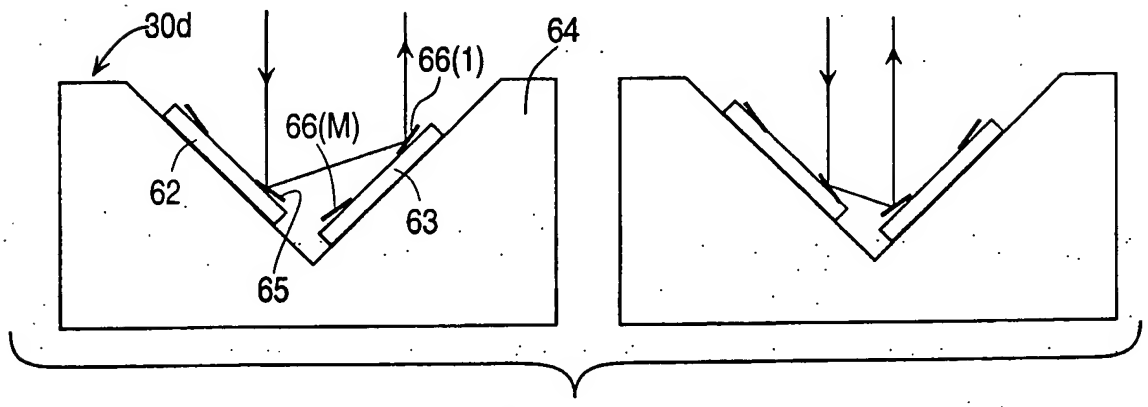

FIG. 5B

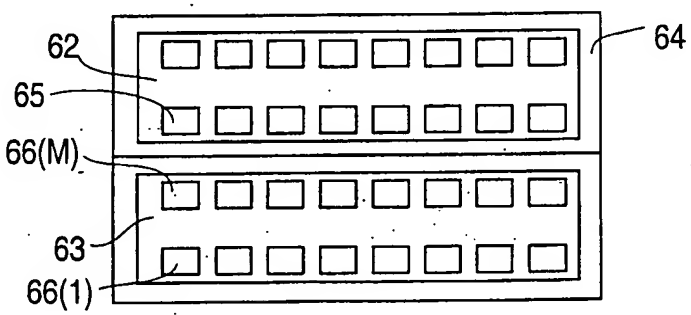

FIG. 5C

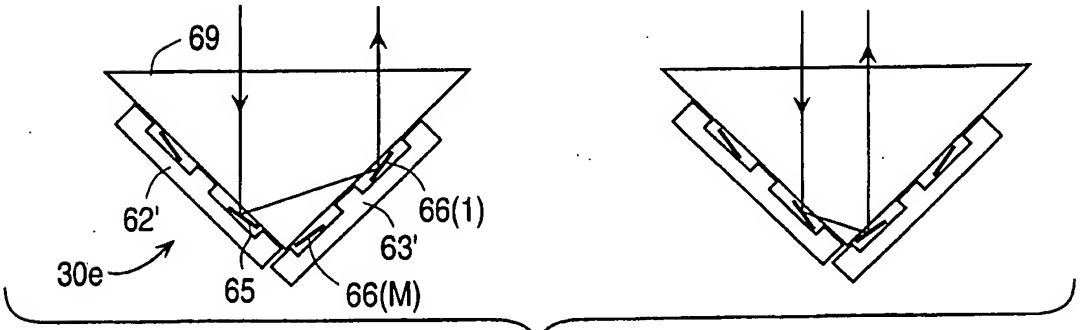

FIG. 5D

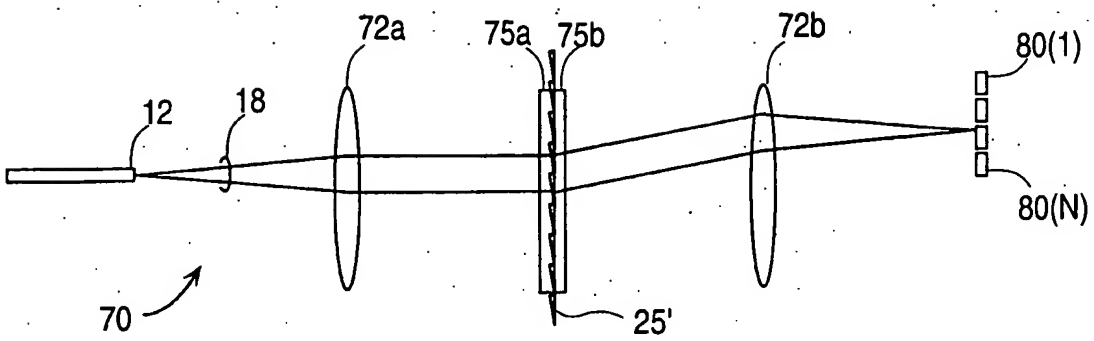

FIG. 6A

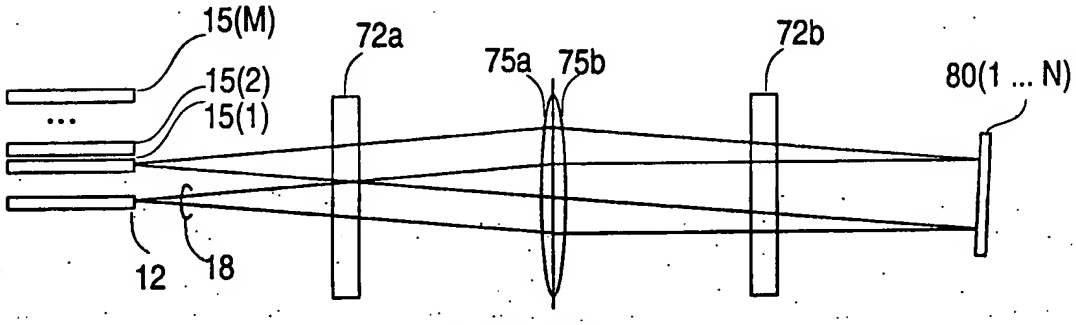

FIG. 6B

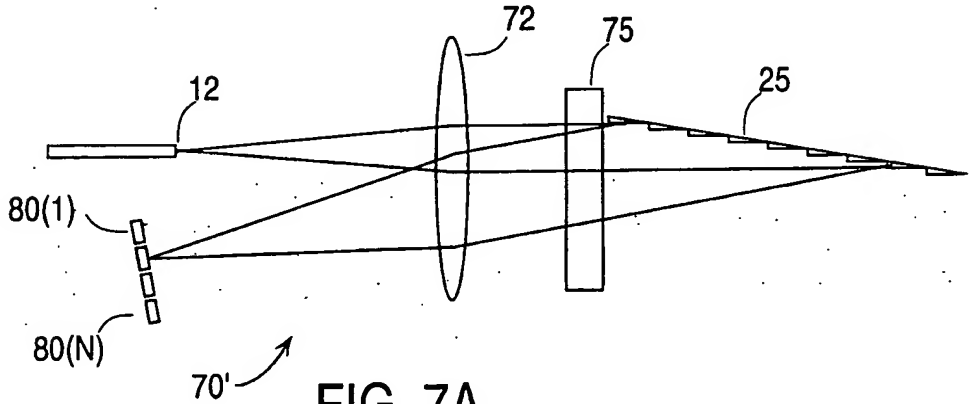

FIG. 7A

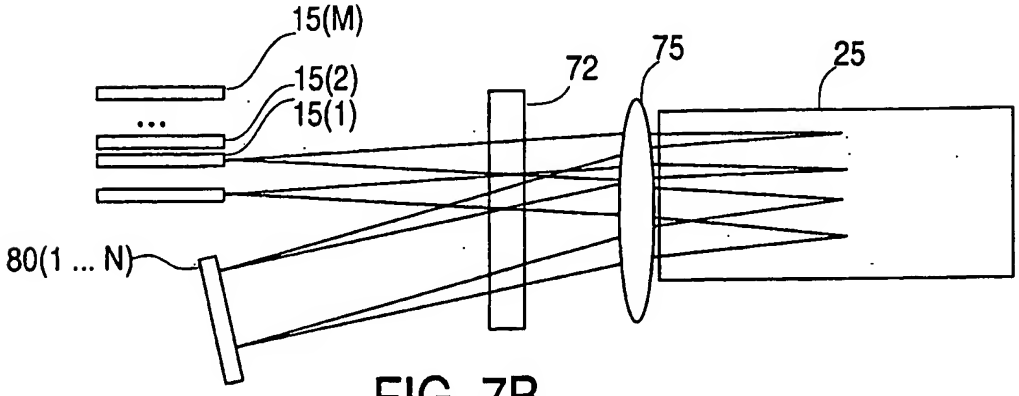

FIG. 7B

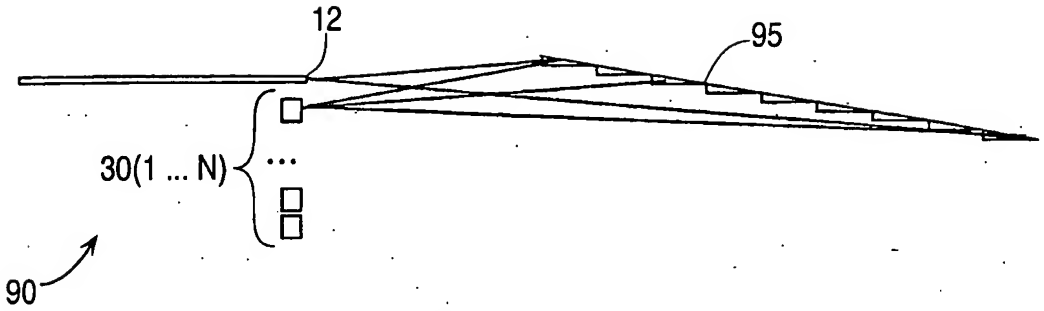

FIG. 8A

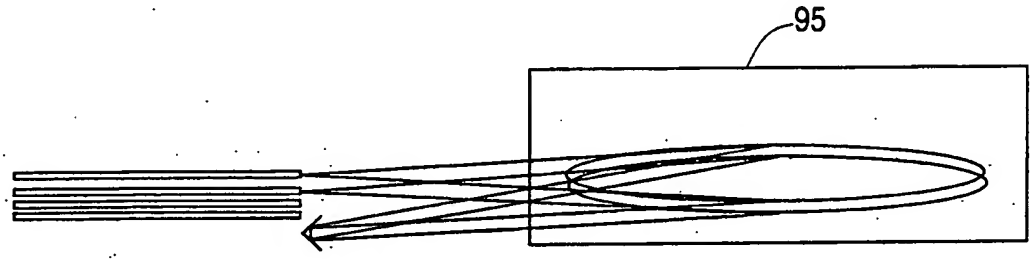

FIG. 8B

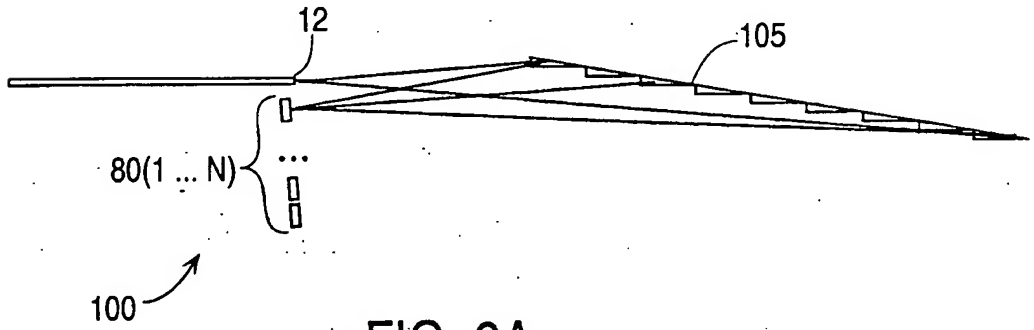

FIG. 9A

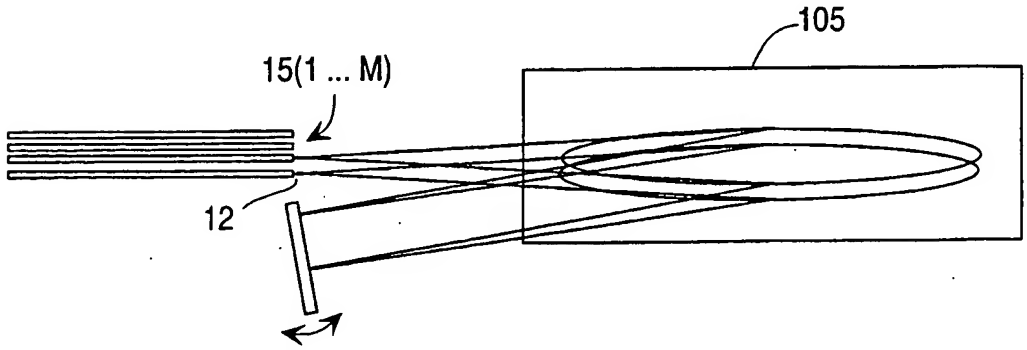

FIG. 9B

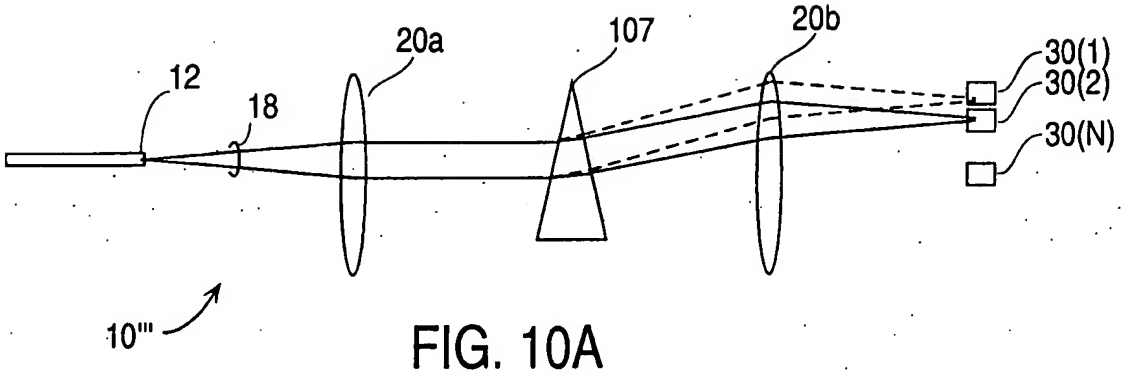

FIG. 10A

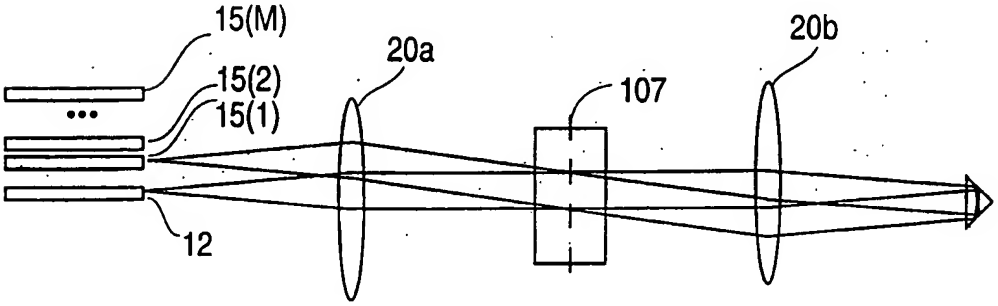

FIG. 10B

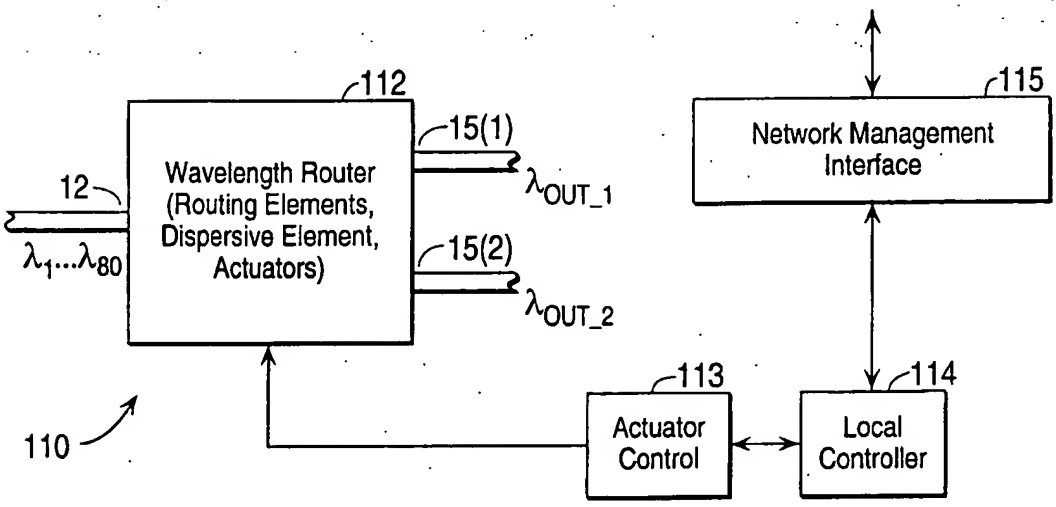

FIG. 11

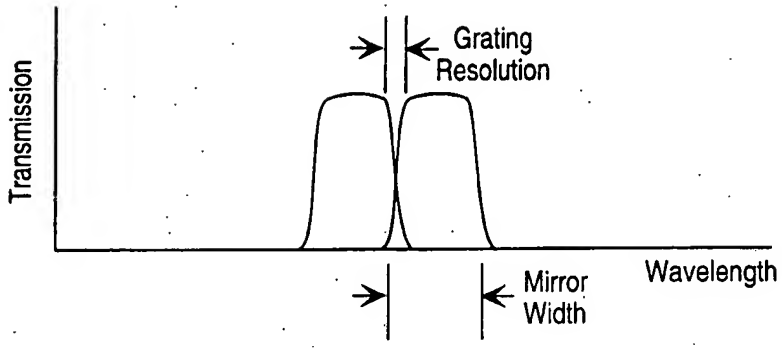

FIG. 12A

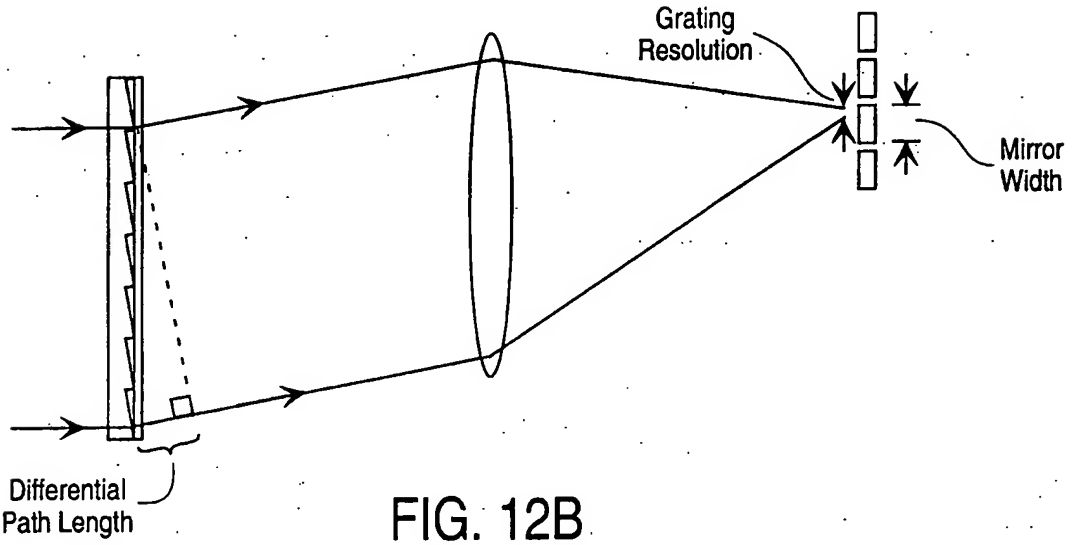

FIG. 12B

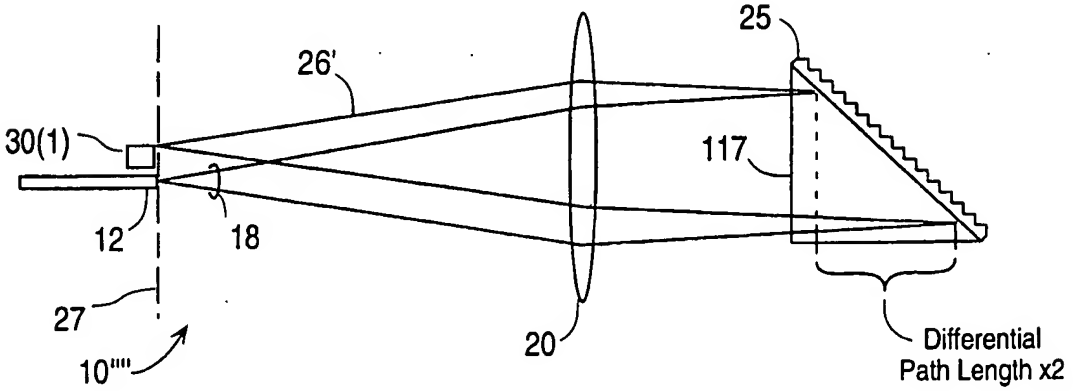

FIG. 12C

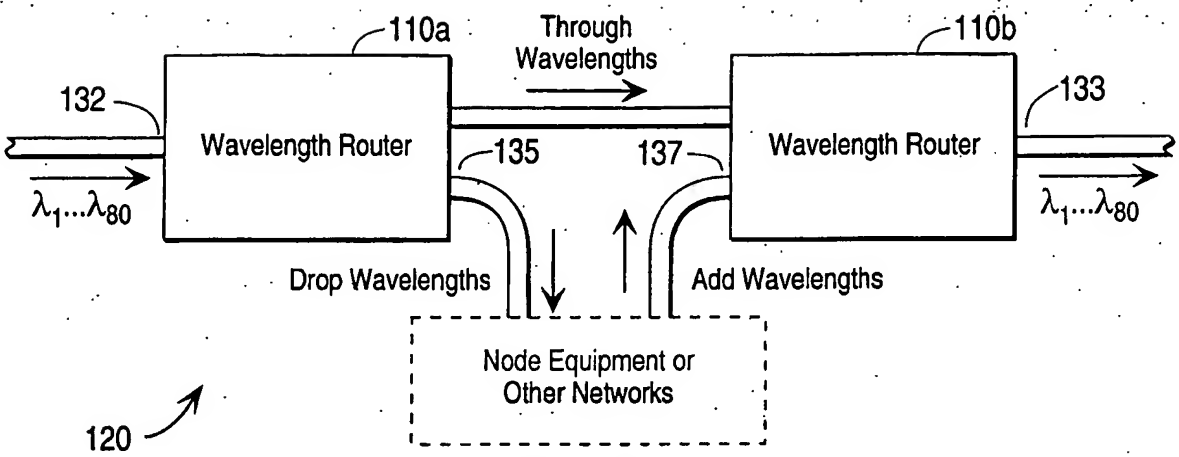

FIG. 13

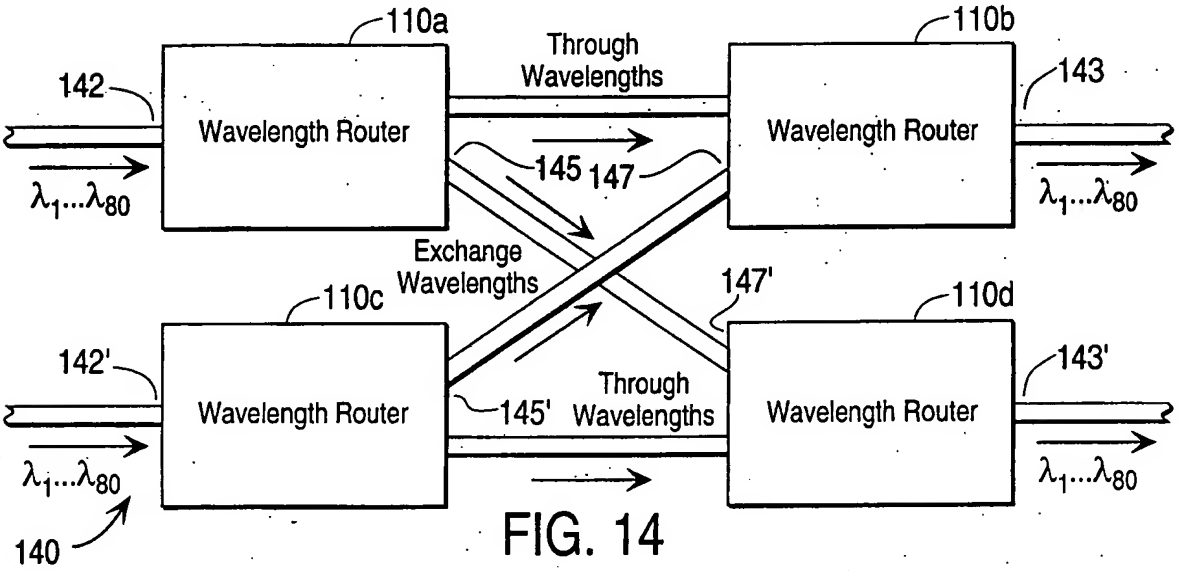

FIG. 14

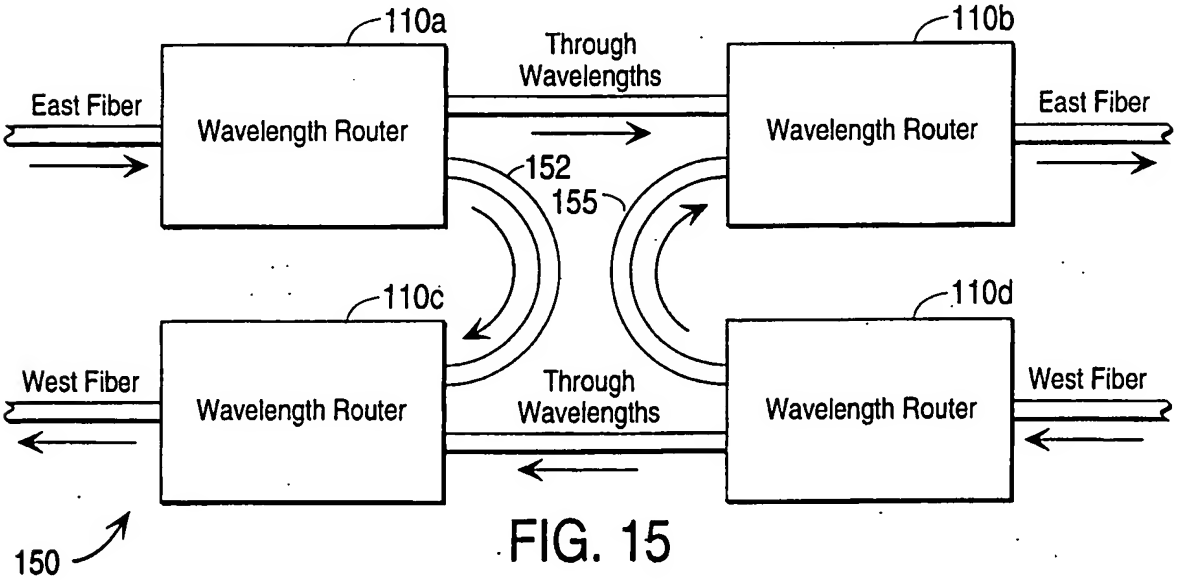

FIG. 15

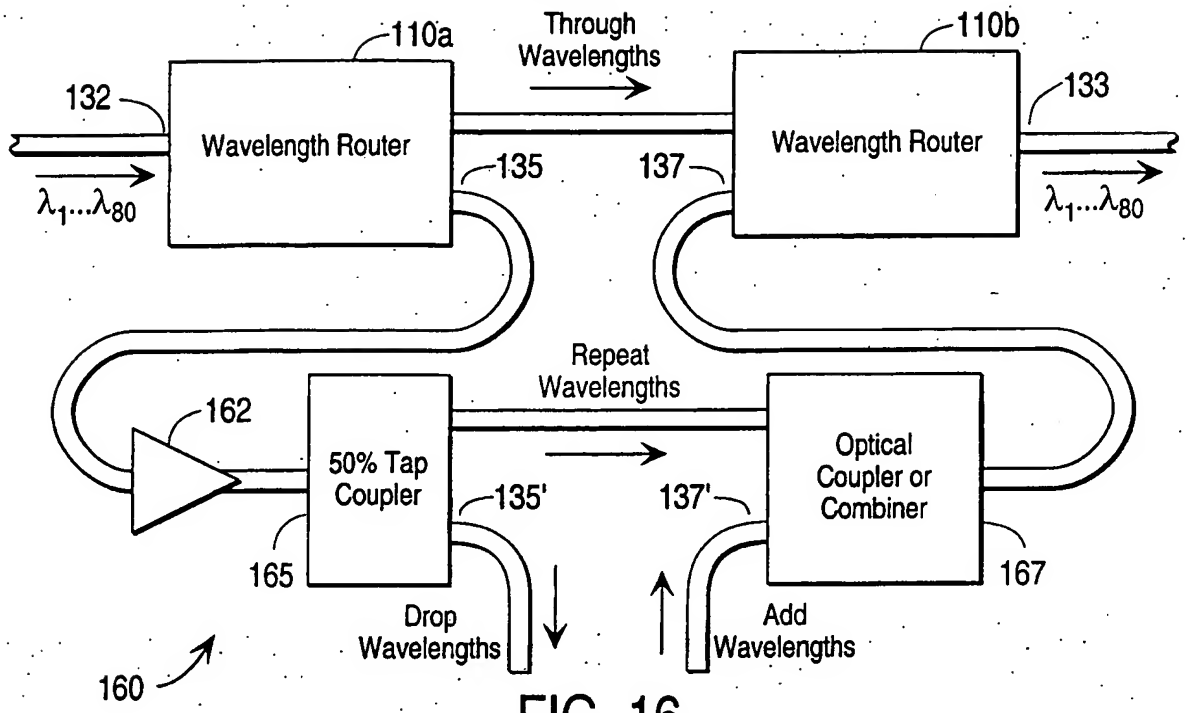
110a
Through Wavelengths
110b
132
Wavelength Router
Wavelength Router
133
135
137
$\lambda_1...\lambda_{80}$
$\lambda_1...\lambda_{80}$
Repeat Wavelengths
162
50% Tap Coupler
Optical Coupler or Combiner
135'
137'
165
167
Drop Wavelengths
Add Wavelengths
160

FIG. 16

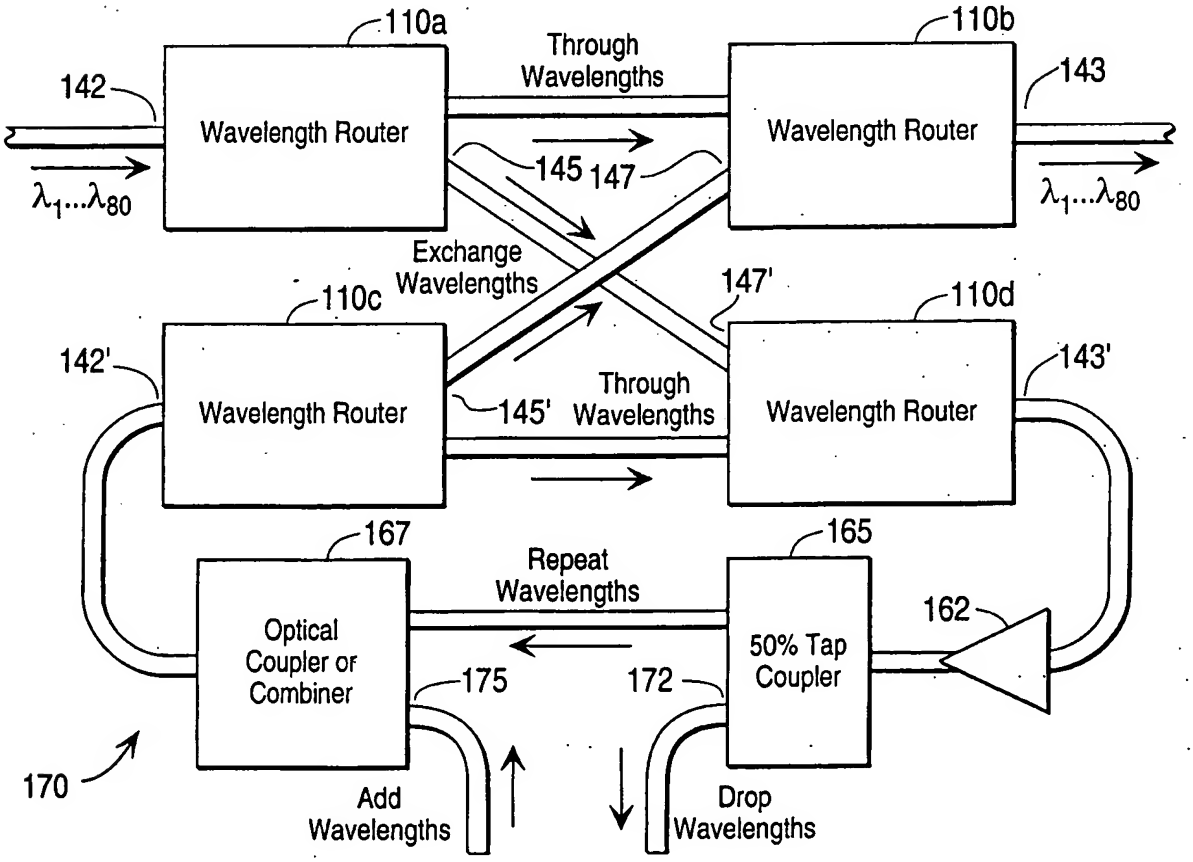
110a
Through Wavelengths
110b
142
Wavelength Router
Wavelength Router
143
145
147
$\lambda_1...\lambda_{80}$
$\lambda_1...\lambda_{80}$
Exchange Wavelengths
147'
110c
110d
142'
Wavelength Router
145'
Through Wavelengths
Wavelength Router
143'
167
165
Repeat Wavelengths
Optical Coupler or Combiner
50% Tap Coupler
162
175
172
170
Add Wavelengths
Drop Wavelengths

FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/31448

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G02B 6/42, 6/26, 6/28; H01S 3/08; H04J 14/02
US CL : 385/24, 31, 18; 359/124 ; 372/100
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 385/16, 18, 19, 21, 24, 31, 47; 359/124,127 ; 372/100; 264/1.7

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

USPAT, EPO, JPO

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,960,133 A (TOMLINSON) 28 September 1999 (28.09.1999), Fig. 2, Fig. 5, column 5 lines 49-54	1-7,9,10,11,16,21 --- 8,12-14,17-20,22-30
Y	US 5,917,625 A (OGUSU et al) 29 June 1999 (29.06.1999), Fig. 5, column 4 lines 14-25	25-27,29-30
Y,P	US 5,999,672 A (HUNTER et al) 07 December 1999 (07.12.1999), Fig. 1, Fig. 2	22,25
Y,P	US 6,097,519 A (FORD et al) 01 August 2000 (01.08.2000), Fig. 6	22
A	US 6,108,471 A (ZHANG et al) 22 August 2000 (22.08.2000), Fig. 1, abstract	1-14,16-30

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 08 FEBRUARY 2001	Date of mailing of the international search report APR 05 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer SUNG PAK Telephone No. (703) 308-0956

Form PCT/ISA/210 (second sheet) (July 1998)*

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/31448

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,903,687 A (YOUNG et al) 11 May 1999 (11.05.1999), Fig. 2, Fig. 10	31-35
Y	US 5,481,631 A (CAHILL et al) 02 January 1996 (02.01.1996), Fig. 1	31-35
Y,P	US 6,097,859 A (SOLGAARD et al) 01 August 2000 (01.08.2000), Fig. 1, Fig. 2, abstract	31-35
Y	US 4,507,790 A (NETTLETON et al) 26 March 1985 (26.03.1985), Fig. 1, abstract	36-38
X ---- Y	US 5,748,811 A (AMERSFOORT et al) 05 May 1998 (05.05.1998), Fig. 13, Fig. 14	15,39,43 ---- 40-42,44,45
Y,P	US 6,069,719 A (MIZRAHI) 30 May 2000 (30.05.2000), Fig. 1, abstract	41,42,44,45

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/31448

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/31448

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single inventive concept under PCT Rule 13.1. In order for all inventions to be searched, the appropriate additional search fees must be paid.

Group I, claim(s) 1-14, 16-30, drawn to a wavelength router.
Group II, claim(s) 31-35, drawn to a configurable retroreflector array.
Group III, claim(s) 36-38, drawn to a method of making an array of rooftop prisms.
Group IV, claim(s) 15, 39-42, drawn to an add-drop multiplexer.
Group V, claim(s) 43-45, drawn to a wavelength-selective cross-connect.

The inventions listed as Groups I through V do not relate to a single inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

The special technical feature of the Group I invention is the specific structural components making up a wavelength router. The special technical feature of the Group II invention is the specific structural components making up a configurable retroreflector array. The special technical feature of Group III invention is the method steps involved in making an array of rooftop prisms. The special technical feature of Group IV invention is the specific connection arrangement comprising an add-drop multiplexer. The special technical feature of Group V invention is the specific connection arrangement comprising a wavelength-selective cross-connect. Since the special technical features of Groups I through V are only present in each invention groups and do not exist in any other groups as claimed, unity of invention is lacking.